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## Summary

This document was compiled in response to the suggestion made by the DOE SC Review of the NSLS-II Project on April 2012, and reiterated at the Review in July, 2013.

The main contributors to this document are the SR magnet team[A] and other in-house participants in the Workshop[B] referred to below that took place on April 11th and 12th 2012 at BNL. The contributions also came from some external participants, including representatives of some of the suppliers who attended the workshop.

Manufacturing of the magnets for the NSLS-II storage ring (~850 units of 15 types) took approximately 6 years from the beginning of the conceptual design to completion of manufacturing in October of 2012. The production in the early years did not go smoothly, and a DOE Review Committee expressed concerns in November of 2010 about the potential for significant delays in magnet deliveries. In response, the project undertook three major mitigation steps: 1) enhanced oversight by assignment of one technical representative for each of the seven suppliers, 2) appointment of a senior BNL scientist as the manager of the SR magnet production, and 3) streamlining the decision-making process.

These steps led to a successful completion of magnet production and delivery with almost all magnets meeting their specifications (see Appendix 2).

## Lessons Learned

The SR Magnet Team learned several important lessons from its interactions with the NSLS-II physicists, engineers, procurement staff, and the magnet suppliers. These are summarized below and presented in more detail in the sections that follow.

- **Magnet Lattice Design** – The magnet lattice should be finalized and documented (in a controlled document) as early as possible, especially before the magnet procurement phase. The lattice design should be optimized to reduce the number of different types of magnets.

- **Specifications** – Specifications must be concise, clear and verifiable. All necessary requirements and dimensions must be given with appropriate tolerances. Magnetic field specifications should be driven by the performance requirements of the machine, not by what might be achievable or what is reported in the literature for similar machines.

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[A] The team consisted of John Escallier, Frank DePaola, Tom Dilgen, Lewis Doom, Weiming Guo, Animesh Jain, George Rakowsky, Satoshi Ozaki, Sushil Sharma, John Skaritka and Charles Spataro, all from BNL, and Luke Adamson and Klaus Sinram, both magnet consultants.

[B] See Appendix-1 for the list of participants and the link to the workshop.

- **Preliminary/Reference Designs** – The preliminary/reference designs need to be very specific regarding the magnet's critical envelope dimensions and interface details (with vacuum chamber, girder and utility connections). For other aspects of the design the suppliers should be given considerable flexibility to meet the performance specifications.

- **Prototype Program** – For a successful prototype program, a thorough in-house testing of the prototype magnets is essential. This requires advanced preparation of the testing facility, including the magnetic measurement setup. The procurement program should be setup to leverage the experience gained in building the prototype magnets.

- **Procurement Strategy and Selection of Suppliers** – The numbers of suppliers should be limited to no more than three, to keep the effort required in technical assistance and production monitoring at a reasonable level. An attempt should be made to split the production of any specific magnet type between two suppliers.

- **Magnet Designs** – Most of the suppliers did not change the reference designs significantly. These designs had some weak features, such as iron-starved yoke and multiple mating surfaces, which went unnoticed by the suppliers.

- **Magnetic Measurements** – A strong magnetic measurement capability was crucial to ensuring the field quality of the magnets and in resolving several technical issues.

- **Manufacturing Issues** – Several of the manufacturing issues were technical, such as de-bonding of the dipole yoke laminations and field reproducibility after magnet splitting and reassembly. In such cases, a close technical interaction was required between the SR Magnet Team and the suppliers.

- **Monitoring Progress** – Besides weekly conference calls, extended visits to the supplier facility to resolve technical issues and establish high-level rapport with the suppliers' top-level management were found to be highly productive.

- **Assembly and Interference Issues** – Detailed 3D models that combine the suppliers' magnet designs with the girders, supports and chambers should be prepared and kept up to date in order to avoid costly assembly and interference issues. Magnet designs should take into account the process of magnet splitting (to install vacuum chambers) and reassembly.

- **Magnet Alignment** – The magnets should be properly fiducialized to meet the alignment requirement and to take advantage of modern alignment techniques.

- **Transportation Issues** – Suppliers' designs of the shipping crates, shock and temperature sensors, and shipping methods should be evaluated and approved. A pre-shipment checklist should be prepared by the supplier for approval before shipping authorization is granted.

- **Construction Spare Magnets** – Spare magnets for the construction phase should be included in the original contracts to avoid unexpected delays during the final months of magnet-girder assembly and accelerator commissioning. Unused construction spares are transferred to Special Process Spares after the project completion.

- **Magnet Database and Travelers** – An online database should be available to store the extensive number of documents, datasets, and travelers generated during the magnet procurement.

## Introduction

The NSLS-II 3-GeV storage ring is 792m in circumference, comprised of 30 Double Bend Achromatic (DBA) cells. Between DBA cells there are 15 long straights and 15 short straight sections for the installation of insertion devices, with two of the long straights reserved for the superconducting RF cavities and another long straight reserved for the injection hardware. Each DBA cell consists of two dipole girders, each holding a 2.6-m long, 6º-bend dipole, and three multipole girders that hold a number of quadrupoles, sextupoles, and corrector magnets. There are 16 types of magnets used in the DBA cells. The quantities of magnets and the supplier of each type are listed in Table 1.

**Table 1:** Types of NSLS-II storage ring magnets, the number required, and the supplier of each type.

| Magnet Type | Qty | Supplier |
|---|---|---|
| Dipoles: 35 mm gap | 54 | Buckley Systems Inc., New Zealand |
| Dipoles: 90 mm gap | 6 | |
| Quads: single-coil, short, narrow | 30 | Budker Institute of Nuclear Physics, Russia |
| Quads: single-coil, short, wide | 30 | |
| Quads: double-coil, long, narrow | 30 | |
| Quads: double-coil, long, with cut-out | 30 | |
| Quads: double-coil, short, narrow | 30 | Tesla Engineering, UK |
| Quads: double-coil, short, wide | 90 | |
| Quads: large aperture | 60 | Buckley Systems Inc., New Zealand |
| Sextupoles: narrow | 169 | Danfysik, Denmark |
| Sextupoles: wide | 75 | Inst. of High Energy Physics, Beijing, China |
| Sextupoles: large aperture | 30 | Buckley Systems Inc., New Zealand |
| Correctors: 100 mm X/Y | 102 | Everson-Tesla, USA |
| Correctors: 100 mm X/Y/Skew Q | 30 | |
| Correctors: 156 mm X/Y | 60 | |
| Air core correctors | 90 | Sag Harbor Industries, USA |

Altogether, construction of the NSLS-II storage ring involved the manufacture of 826 magnets, undertaken by seven manufacturers from six countries around the globe. The procurement of these magnets was done by the usual open bid method prescribed in the Federal Acquisition Regulations (FAR). The request for proposal (RFP) was based on performance specifications and reference designs that defined the interface conditions relative to the outside environment—such as the dimensions that the magnet can occupy, and its water, electrical, and girder connections. The selection of the suppliers was on the basis of best value to the project.

The magnetic field specifications of the NSLS-II magnets are stringent, being driven by the high-brightness and dynamic-aperture requirements, but they are not unrealistically tight, compared to those of recently built light sources. Based on the proposed physics lattice of the ring, the preliminary designs of the magnets began in late 2006. The first review of preliminary magnet designs by an external committee consisting of Jack Tanabe (SLAC), Jack Jagger (ANL), and Emil Trakhtenberg (ANL) took place on August 6–7, 2007. Incorporating many suggestions the review committee made, the designs of the magnets were developed further. In parallel, extensive discussions took place among the cognizant members of the project and the Laboratory on the procurement method, leading to the conclusion that actual procurement would be done on a build-to-specification basis. After the Prototype Lattice Magnet Design Review on January 28–29, 2008 and finalization of the design, the contract to produce prototypes was signed in May of 2008. However, by the time the prototype magnets were delivered in early 2009, not enough time was left to perform critical and in-depth studies of these magnets.

The initial set of seven RFPs covering the manufacturing of complete storage ring magnets was issued during May and June of 2009. After the best-value-based selection of the proposals and negotiations with selected suppliers, the procurement contracts were signed in late September and October of 2009, with the first articles to be delivered by April to June of 2010. However, only one of the seven suppliers could deliver acceptable production-quality first articles by the time of the DOE SC Review held on November 15–17, 2010. The review committee expressed its concerns in the following recommendations:

- The Project should aggressively pursue mitigation plans that were presented.
- Explore other options immediately, such as deployment of an experienced engineer at a supplier’s facility to receive first-hand and real-time feedback.
- Ensure that necessary resources (budgetary and manpower) are assigned to resolve the magnet production problems.

Based on these recommendations the project took the following mitigation steps:

1. **Enhanced Oversight** – One technical representative was assigned to each of the magnet suppliers, a major change from one engineer being the technical representative for all seven suppliers. In addition, an experienced magnet engineer was stationed at the facility of one of the suppliers and another experienced magnet consultant supported all technical representatives.
2. **Manager of SR Magnet Production** – A senior BNL scientist with considerable accelerator project management experience was appointed as the manager of SR magnet production. He directed the SR Magnet Team, established high-level liaison with the suppliers’ management, took on procurement decisions, coordinated resolution of technical issues, and established back-up production plans.
3. **Decision Making**− Technical and production issues were resolved directly between the SR Magnet Team and the magnet suppliers with BNL procurement staff providing contractual guidance. This was in contrast to all communication with the suppliers being conducted by the procurement staff.

There were still rather lengthy and tortuous delays in the production and delivery of the first article magnets that met the specifications. However, the production began to run relatively smoothly in the spring of 2011. The production of all magnets was completed by October 2012, in time such that the installation of all magnet-girder assemblies in the storage ring tunnel was completed on schedule in January of 2013.

An analysis of the magnetic fields, as expressed in the magnitude of allowed and un-allowed higher harmonics, has shown that the statistical distribution of the harmonics errors in all the magnets produced is essentially within the specifications (Appendix 2). However, there are a number of lessons that we have learned in this process regarding what was effective in bringing this program to a successful completion, what could have made this task easier, and what was not helpful and should have been avoided.

Noting that fabrication of the magnets for the NSLS-II storage ring by the manufacturers worldwide would be occurring near the end of the scheduled period, a workshop was held at BNL on April 11 and 12, 2012. The purpose of this workshop was partly to celebrate our reaching this important milestone, and partly to share the knowledge and experience gained by everyone involved in this endeavor.

This report records the major lessons learned that were reported at the workshop mentioned above, including those learned by our magnet team in the process of managing the NSLS-II magnet production. These lessons learned include the inevitable “Things could have been better if … .” items. The document is organized into the following topics that surfaced as the production progressed

- Machine Lattice Design
- Magnet Specifications
- Preliminary/Reference Designs
- Prototype Program
- Procurement Strategy and Selection of Suppliers
- Magnet Designs
- Manufacturing Issues
- Magnetic Measurements
- Monitoring Progress
- Assembly and Interference Issues
- Magnet Alignment
- Transportation Issues
- Construction Spare Magnets
- Magnet Database and Travelers

## 1 Machine Lattice Design

The machine lattice should be stabilized as early as possible, preferably before the start of the procurement process for the magnets, girders, and vacuum chambers. Frequent and late changes in the machine lattice complicate the engineering design and procurement of the magnets, as well as of the girders and vacuum chambers. Some of the major changes to the NSLS-II lattice that were substantially late are: 1) changing the apertures of some of the multipole magnets on the dispersion girder, leading to a ‘large aperture’ in the quadrupoles and sextupoles in order to improve the field quality in the dispersion region; 2) reconfiguration of the number and location of the corrector magnets; and 3) elimination of a family of sextupole magnets.

There was a strong push to make the lattice as tight as possible to reduce the circumference of the ring in order to reduce the overall cost. The decisions regarding free space between the magnets should have been taken with close interaction between the machine physicists and the engineers. Some of the earlier NSLS-II lattices were found to be too tight to accommodate the physical sizes of the magnetic elements, and subsequently a larger but uniform spacing between the multipole magnets was adopted without proper consideration given to the chamber supports, beam position monitors, radiation absorbers and vacuum pumps. While technical solutions were found to all issues that were encountered, (e.g., replacing the slightly-magnetic Invar chamber supports with carbon-fiber supports), a realistic non-uniform spacing between the magnets would have been a better option, taking into account all accelerator components on the girders.

Strong consideration should be given to reducing the number of different types of multipoles and correctors in the design of the machine lattice. The NSLS-II lattice has seven types of quadrupoles, three types of sextupoles, and three types of iron-core correctors. In comparison, it should be noted that the APS lattice had four types of quadrupoles and a single type of sextupole and iron-core corrector. Each new type of magnet requires additional resources in engineering design, procurement, testing, and spares, which should be taken into account in the overall optimization of the lattice design. Additionally, a large number of different types of magnets can impact the girder assembly schedule if some suppliers fall behind in their delivery schedules.

## 2 Magnet Specifications

Magnet specifications describe form, fit, and functions of the magnets to be manufactured and must be concise, clear, and verifiable. They need to include only the necessary dimensions (for example, envelope dimensions containing the magnet) and performance parameters, all with appropriate tolerances.

The initial magnet specifications lacked clarity in some areas. No tolerances (maximum, minimum, or range) were specified for the magnetic length, power dissipation, and current density in the copper conductor. The tolerance on the integrated field was specified incorrectly as maximum required rather than minimum. In most cases, storage ring magnets for a light source will be split for installation of vacuum chambers. The initial specifications did not call out the magnetic field quality reproducibility under reassembly, other than an assembly tolerance of 5 µm, which was unnecessarily stringent and difficult to verify. The yoke-length variation from magnet-to-magnet was not specified, but was subsequently deemed to be important. The field specifications were specified only at the maximum current for the magnet, not for the entire operating range. A secondary entity, magnetic length, was specified rather than the primary entity, integrated magnetic field. The specifications for the water flow, pressure drop, and temperature rise were over-constrained. Use of the phrase "or equivalent" in the specifications for some items (e.g., epoxy formulation) caused protracted discussions with suppliers.

The initial field specifications of the NSLS-II multipole magnets were quite ambitious, and could only be met with special machining and assembly techniques. The implementation of these techniques in the production environment was found to be quite challenging and led to the initial delays in the magnet procurement.

The field specifications were established on the basis of published field specifications of some recent light sources (Soleil and SLS, specifically) to ensure that the adopted specifications would meet NSLS-II storage ring requirements. The initial NSLS-II field specifications were especially exacting for the mid-range harmonics ($5<n<12$), requiring secondary machining such as EDM, or milling or precision-stamping of the pole faces. When magnet suppliers started having technical issues in meeting the initial specifications, a systematic study was carried out to relax the field specifications. In hindsight, a comprehensive field tolerance study to find the best compromise between cost and performance should have been done at the outset.

The symmetry-allowed terms, which can be reduced to almost zero by computational optimization of the pole profile, could have been tightened to ~1 unit ($1\times10^{-4}$). These terms for the magnets built for Soleil and ALS-upgrade are close to zero even without secondary machining.

The initial specifications were revised three times. Nevertheless, the imprecision in the magnet specifications, especially with regard to epoxy formulation and magnet reproducibility, led to significant adverse impact on magnet designs, production, acceptance tests, and documentation.

## 3 Preliminary/Reference Designs

To ensure that the lattice magnets can be properly integrated with the support system, vacuum chambers, and utilities, it is necessary to develop preliminary, or reference, designs of the magnets. Even if the complete designs are subsequently developed by the magnet suppliers, it is critical that reference designs are developed to a stage that they precisely define interface requirements—namely, the aperture, overall physical dimensions (especially the length), utility connections, and magnet-to-girder support configuration.

The dimensional envelopes of the reference designs must ensure that the magnets do not saturate, or have only an acceptable level of saturation, at their maximum fields. They must also be consistent with the structurally robust designs of the magnets in order to ensure field reproducibility under reassembly when the multipole magnets are split for inserting the vacuum chambers and then reassembled.

The most important factor that affected the production of the NSLS-II magnets of all types was that the dimensional envelope of the reference designs was inadequate, thus making the magnets iron-starved and structurally weak. Because of a lack of resources, detailed nonlinear magnetic analyses and structural analyses were not carried out, especially for the dipoles and quadrupoles, to identify and correct these weaknesses in the reference designs. It was assumed that the magnet suppliers would perform such analyses, and would rectify any problems that would be identified. Most of the magnet suppliers, however, assumed that the supplied reference designs were adequate and did not spend their resources to optimize them. One of the quadrupole suppliers, even with the knowledge that the pole profile supplied in the

NSLS-II reference design was not optimum, decided not to change the profile, assuming erroneously that such a change was not allowed.

One approach that was initially considered in the magnet program, and that in retrospect has considerable merit, is to completely define the magnet yokes in the reference designs in terms of their dimensions, tolerances, lamination material, stacking, precision machining and assembly. The magnet supplier is then given considerable flexibility in designing other components of the magnet, such as coils, as well as the internal arrangement of utilities such as piping, bus bars, and instrumentation wiring.

## 4 Prototype Program

An extensive prototype program was undertaken in the spring of 2008 consisting of two dipoles, five quadrupoles and three sextupoles, representing various configurations of these magnets. The magnets were built by three suppliers (Stangenes Industries, IHEP Beijing, and Buckley Systems, Inc.) by March of 2009. The prototype program provided valuable insight toward several aspects of the magnet production; namely, it: 1) established the capabilities of the participating suppliers, 2) identified some of the technical and manufacturing issues, and 3) provided a basis both to BNL and the suppliers about the expected field quality, cost, and schedule for the production magnets.

However, the delivery of the prototype magnets and the procurement process for the production magnets revealed several weaknesses of the prototype program. The most important of these arise from the FAR requirement of not allowing a magnet supplier that built the prototypes to participate in the open bidding for the actual production. This stipulation had already led some of the important suppliers not to actively participate in the prototype program. Another supplier who did participate chose not to spend its resources on tooling and fixtures. Yet another supplier who had participated successfully in building several prototype magnets chose not to submit proposals for the production magnets.

The prototype program also suffered from some missing or imprecise magnet specifications (e.g., magnet saturation, field reproducibility after reassembly, tolerances on the specified values), and from a lack of formal acceptance procedure. Although the magnet measurement program at BNL had been resurrected, it was still hampered by a lack of resources and procedures. The prototype magnets, therefore, did not go through full testing and many weak design features (see Section 7) of these magnets could not be identified.

In the end, the Project and most of the magnet suppliers entered into building the ‘first article’ magnets without the benefit of having built the prototypes and without being aware of some of the important deficiencies of the prototype magnets. The first article magnets were essentially the prototypes that the suppliers used to verify their designs and production methods. This raises the question of whether the prototype program could have been eliminated—notwithstanding its useful features—and integrated into the first-article phase of the magnet procurement. This approach is strongly recommended when adequate resources are not available to perform in-house design and testing of the prototypes.

When a project has sufficient technical depth and resources, a better strategy could be to design and build one representative prototype of each type of magnet (dipole, quadrupole, sextupole, and corrector). Once the prototypes have been thoroughly tested to ensure their robustness and manufacturability, the procurement of the production magnets could proceed with the selected suppliers, with yokes and interfaces (mounting and utility connections) built-to-print, and other details (such as coils) covered by performance specifications.

## 5 Procurement Strategy and Selection of Suppliers

As mentioned in the Introduction, the NSLS-II SR magnets have been built by seven suppliers from six countries. Considerable resources were spent to evaluate the suppliers based on their expertise, past experience, manufacturing capacity, in-house QA program, and their proposals. However, as the magnet production moved forward, it became clear that the selection process had some weaknesses.

We found that when suppliers claimed an excellent track record on magnet manufacturing in response to the RFP, it did not necessarily mean they had the engineering expertise in place at the time of their response. Since large-scale accelerator magnet productions are not a steady business, the suppliers need to reassign their expert magnet engineers to other jobs or risk losing them. As it turned out later, all suppliers required substantial assistance from the BNL team to resolve technical issues in the areas of 3D magnetic analysis, magnetic measurements, field analysis, epoxy potting with SLAC formula, precision machining, and magnet assembly. Many of the technical issues were common to most of the suppliers, and it became very difficult for the BNL team to provide timely technical assistance until the team was substantially expanded at the start of 2011. The lesson learned from this is that a project must be prepared to provide technical and engineering support to the suppliers, and the contract must be written to allow such assistance.

The combination of a large number of magnet types from so many suppliers consumed not only resources in direct support, but also proved to be challenging in keeping up-to-date documentation including 3D models, drawings, test reports, travelers, QA reports, etc., as well as management of the girder assembly schedule. Of course, selecting a single supplier for all SR magnets would have been much too risky for the NSLS-II project. In retrospect, selecting only two or three suppliers for making magnets of all types, with the option of making the first articles, 50% and 100% of the production of each magnet type, would have been preferable. The suppliers' selection would be easier also if the number of different types of magnets were reduced by lattice optimization. A possible contract form that should be looked into is cost plus incentive fee (CPIF) for manufacturing of the first articles and tooling, and firm fixed price (FFP) for the production.

Although traveling distance to the supplier is customarily not accepted as a good selection criterion, managing the oceans-away suppliers for the NSLS-II room-temperature magnets turned out to be much harder than the previous experience of managing a supplier on Long Island for the superconducting magnet production for RHIC.

## 6 Magnet Designs

As mentioned earlier, it was decided to procure the magnets on the basis of built-to-specifications constrained to the dimensional envelopes shown in the Interface Control Drawings (ICDs). The ICDs, however, also showed reference designs (see Fig. 1) that included almost all details of the mechanical design such as shape of the laminations, pole face geometry, and assembly details. In principle, the suppliers could have developed their own mechanical designs, but they were left with the impression that the reference designs were consistent with the specifications and were likely to be readily approved in the design validation and production readiness reviews. Additionally some of the suppliers assumed erroneously that the contractual language in the Statement of Work (SOW) would not have permitted them to make significant changes to the yoke geometry and assembly details.

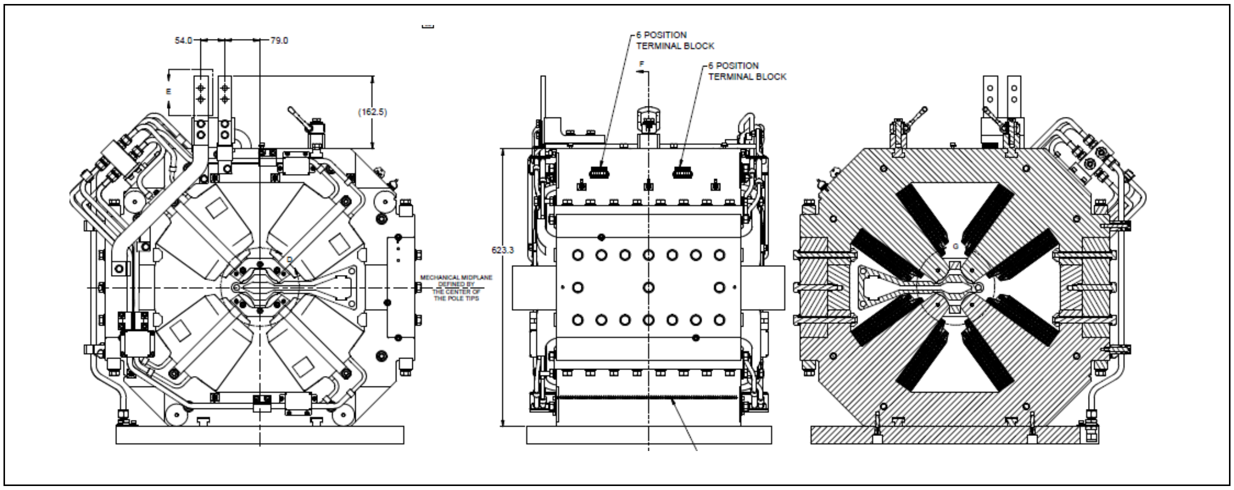


**Figure 1:** Part of the interface control drawings for a quadrupole.

The suppliers were unable to give proper consideration to the following design choices in their magnet designs.

## 6.1 Segmented Pole Design

The reference designs showed the upper and bottom half yokes to be made from laminations containing half the total number of poles (Fig. 1). Because the laminations, after punching, experience ‘creep’ over some time and there are some thermal distortions in the yokes during the curing process, this lamination design essentially dictated secondary machining of the bonded yokes that was time-consuming and expensive. Only one of the suppliers could avoid secondary machining by means of inserting precision-machined copper-chromium bars between the poles to control the pole spacing to within 10 µm. It should be noted that some suppliers use laser-cutting of laminations and secondary machining (EDM) of the yokes as the standard method of magnet production.

The multipole magnet could also be designed as segmented poles (Fig. 2) which could be made from precision-stamped material, with only one pole in each lamination. This approach, which was proposed in the NSLS-II Conceptual Design Report and used for the beam transfer line magnets, could have obviated the need for secondary machining and provided more flexibility in the adjustment of the field harmonics. For the sextupoles, it would also have eliminated the need for ‘removable’ poles for the insertion of coils. Although all suppliers succeeded in manufacturing acceptable sextupoles, the assembly of sextupole magnets with the removable poles within specified tolerances turned out to be a major issue. It would have been much more beneficial to form upper and lower halves of sextupole magnets, each half with three segments of one pole each.

**Figure 2.** Typical segmented-pole design of a sextupole magnet.

## 6.2 Iron-Starved Yoke Profile

The magnet yokes of the reference designs turned out to be iron-starved. The cross-sectional envelopes defined in the ICDs were unduly restrictive and, for the most part, unrelated to physical constraints of the storage ring tunnel, vacuum chambers, and girder support systems. In addition to causing the magnets to be saturated at high currents, the iron-starved profiles led to the following associated mechanical issues:

- The magnets became structurally weak such that they could not be easily reassembled within the specified mechanical tolerances. Considerable effort was spent investigating this issue, and eventually an assembly procedure with specific bolt torques and bolting sequence was developed and prescribed to the suppliers. Basically, to minimize distortions in the yokes, the specified torques on the horizontal bolts (25–30 N.m) were to be applied after the specified torques (50–60 N.m) on the vertical bolts (Fig. 3). For maintaining the torque uniformity, it was important to use simple washers (not lock washers) and to lubricate the bolts.

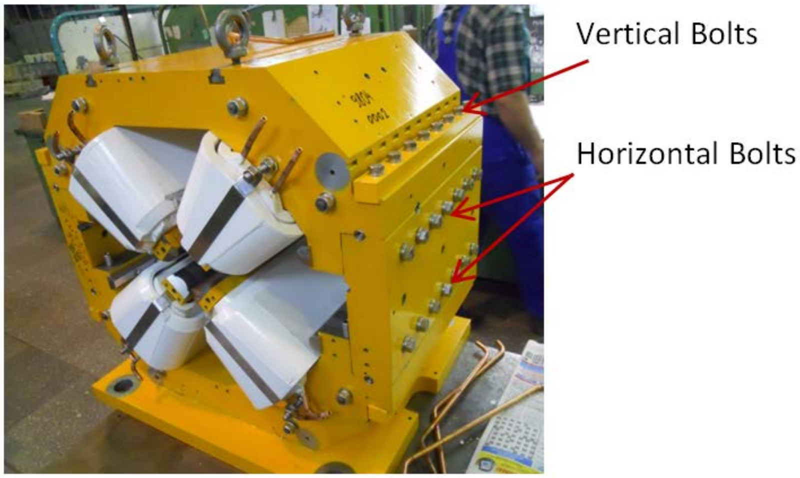


**Figure 3:** Horizontal and vertical bolts for yoke assembly.

- The magnet flux leaked to the baseplates of the multipoles and to the structural plates of the dipoles, causing undesirable field distortions. The understanding and resolution of resulting problems required considerable effort both from the suppliers and the BNL teams. The non-symmetry effect of the bottom baseplate was reduced by one of three methods: 1) introducing an aluminum foil between the yoke and the baseplate, 2) cutting a rectangular hole in the baseplate, and 3) using stainless steel for the baseplate. The structural plates of the dipoles were blanch-ground for a better contact between the plates and the yokes (see Section 8 for additional details).

- Slender cross-sectional areas resulted in weaker bonding strength of the yokes, especially for the 35-mm dipoles. Eight magnet yokes (half of them dipoles) had to be discarded because of unacceptable degrees of separation between the bonded laminations.

## 6.3 Mating Surfaces

The mating surfaces between the magnet half-yokes and the side spacers (Fig. 4a) as presented in the reference designs and adopted by all multipole magnet suppliers, turned out to be a significant manufacturing and assembly issue. Because of manufacturing tolerances, the multiple mating surfaces at right angles could not be in contact without causing distortion in the yokes, and consequently affecting the field quality. The gaps between the vertical contacting surfaces became especially troublesome for reproducibility of the field harmonics. A better yoke design would have specified only horizontal mating surfaces between the side spacers and the half-yokes, shown conceptually in Fig. 4(b). The horizontal bolts would be eliminated in such a design.

The roughness of the mating surfaces, exacerbated by the weakness of the slender yokes, was another assembly issue that was identified and resolved. Essentially the mating surfaces needed to be precision-machined, or ground to ensure reproducibility of the field harmonics.

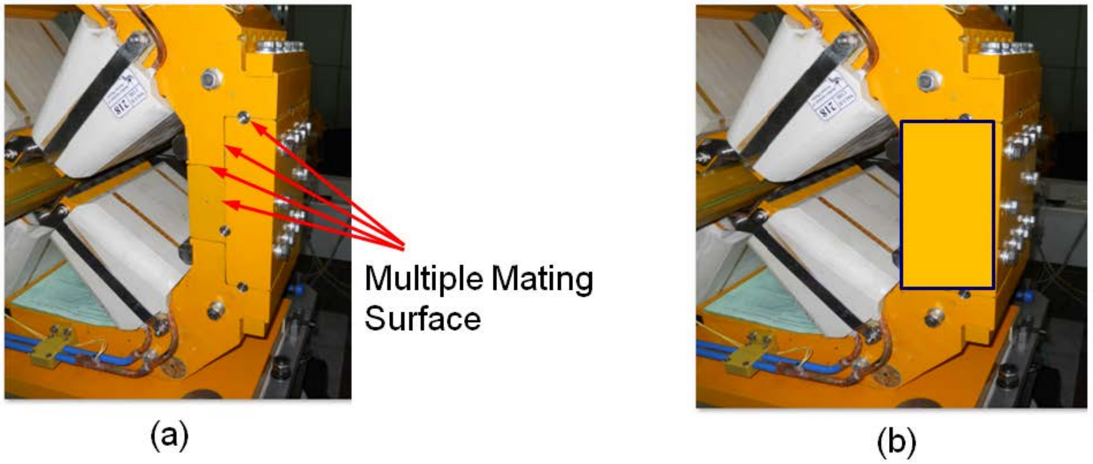


**Figure 4:** Mating surfaces of the magnet yoke.(a) multiple mating surfaces, (b) horizontal mating surfaces only (suggested graphically on original photo).

## 6.4 Pole Clamps

The NSLS-II reference designs showed pole clamps (Fig. 5) that were supposed to assist in maintaining the pole-spacings during assembly and reassembly. The first article magnets received from the suppliers showed several limitations of the pole clamps: 1) the pole-clamp material and clamping hardware was often slightly magnetic, causing unpredictable field quality; 2) the effect of the pole clamps was limited to only the ends of the yokes; and 3) the clearance holes in the pole clamps made them ineffective for maintaining the pole spacings.

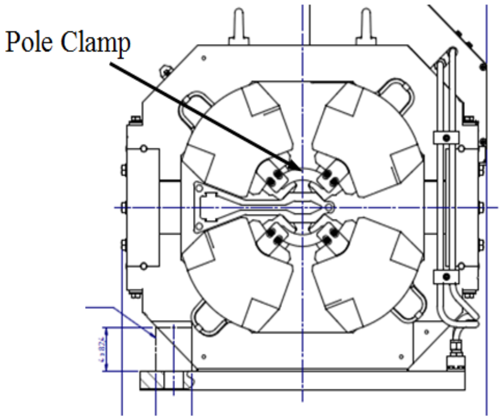


**Figure 5:** Pole clamps in the reference design of a quadrupole.

The effect of pole clamps for reproducibility of the magnetic field was then investigated thoroughly by magnetic measurements at BNL. Following the determination that the pole clamps actually had a slightly adverse impact on the field reproducibility, the suppliers were advised to eliminate the pole clamps.

### 6.5 Coil Holding Clamps

Some of the suppliers used coil-holding clamps that held the coils only by friction. These clamps did not work well, as they frequently became loose due to vibrations and large temperature changes during transportation. Some of the magnet coils that were fastened to the yokes with thin stainless steel straps became loose because of their stretching due to creep. In another design that failed repeatedly and which was eventually replaced, the coil holding brackets were potted in the epoxy of the coils. The epoxy around the bracket cracked under tensile and shear stresses. In the successful clamp designs, the coils were held under compression by the clamps that were screwed to the magnet yokes.

### 6.6 Magnet to Vacuum Chamber Gap

A nominal gap of 1.6 to 2 mm was specified between the magnets and the vacuum chambers to ensure that the chambers would not touch the magnets and affect their positional stability. This value was achievable (with minor exceptions) for the gap between the pole faces and the machined grooves of the vacuum chambers. However, maintaining a 2-mm gap between the magnet coils and un-machined surfaces of the vacuum chambers was found to be problematic because the dimensions of the epoxy-potted coils were difficult to control. The minimum gap between the coils and the vacuum chambers should have been specified as 4 mm (see Sections 10.2 and 10.3 for additional details).

## 7 Manufacturing Issues

During the magnet production the suppliers encountered the following major manufacturing issues.

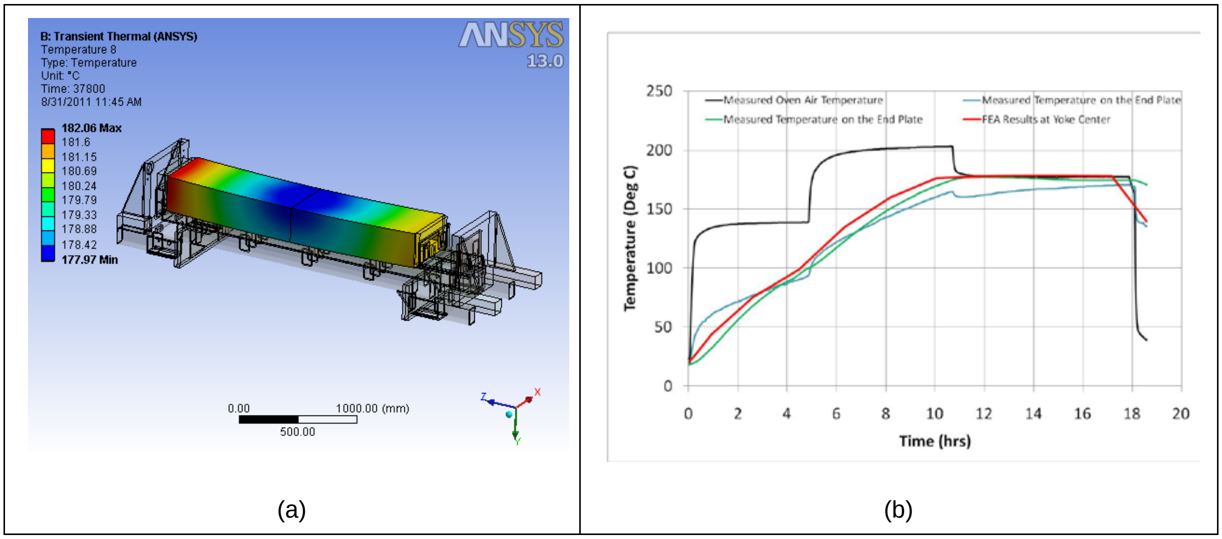
### 7.1 Epoxy Potting of Magnet Coils

The magnet specifications required the suppliers to epoxy-pot the coils with materials and procedures that “conform to the SLAC Potting Epoxy #2 formula and procedure.” Basically this formulation uses 50% alumina in the epoxy mix in order to enhance the radiation hardness of the cured epoxy. The suppliers interpreted the language used in the specification to give them the option of using their own material formulations and procedures. The suppliers who had insufficient previous experience of using the SLAC formula encountered numerous problems during the learning phase, including: 1) epoxy not filling the mold because of the high viscosity and quick-setting time of this formulation, 2) alumina not flowing through the narrow gaps, 3) substantial voids in the cured epoxy, and 4) epoxy not separating easily from the mold after curing. These problems were eventually resolved by 1) sticking closer to the SLAC formulation and procedure, 2) shortening the mixture pouring time relative to the epoxy curing time, 3) using proper techniques for vacuum impregnation, and 4) optimizing the mold geometry and spacers to ensure a proper gap between the mold and the coil.

### 7.2 Bonding of the Magnet Yokes

One of the suppliers experienced difficulties in achieving proper bond strength between the laminations. The lamination-steel supplier, ThyssenKrupp AG, recommends a uniform stacking pressure of 3–6 MPa, and an oven curing of 2 hours at 160$^{o}$C, or 1 hour at 180$^{o}$C. The stacking fixture design needs to be such that the stacking force is distributed evenly over the entire surface area of the stacked laminations. To keep the stacking pressure within the recommended range, the total force must be applied at several points by stacks of Belleville washers. The washers must be selected carefully such that they are able to absorb thermal expansion and contraction of the yoke-fixture assembly without a significant change in the stacking force.

The BNL team performed numerous finite element analyses to help redesign the stacking fixture and to determine the time required to reach the curing temperature. Figure 6a depicts the temperature profile from an FE transient thermal analysis for a dipole yoke and fixture assembly. Figure 6b compares the FE results with measurements and shows that it takes about 10 hours to reach the desired curing temperature of 180$^o$C.



(a) (b)

**Figure 6:** Temperature rise in a dipole yoke. (a) Temperature profile in the yoke – FE analysis, (b) temperature rise versus time, comparison of FE analysis with measurements.

## 7.3 Precision Machining

Numerous problems were also encountered by some of the suppliers in maintaining the dimensional tolerances in precision (secondary) machining of the bonded yokes. These problems included: 1) errors in programming the milling/EDM machines, 2) improper selection of wire and tension for the EDM machines, 3) improper fixturing, and 4) improper changing of the cutting tool. Initially these issues were identified by analyzing the field harmonics of the magnets. However, the use of a CMM (Coordinate Measurement Machine) was subsequently found to provide more direct and timely response for resolving these issues.

# 8 Magnetic Measurements

The BNL magnetic measurement facility under the direction of A. Jain played a key role in the successful completion of magnet procurement. Initially, BNL helped several suppliers in the analysis and evaluation of the raw measurement data. During the production phase, magnetic measurements together with Opera FE models were used to identify and resolve a number of technical issues:

- **Validating magnetic designs.** The analytical designs were verified by actual measurements, especially for evaluating the effects of chamfering and shimming.
- **Field reproducibility after reassembly.** Numerous repeatability measurements were performed to verify a bolt torque pattern that produced the required reproducibility of magnetic field quality after the magnets were split and reassembled.
- **Pole clamp material.** Poor field quality in a number of magnets was traced to magnetic permeability of the stainless steel used for the pole clamps.

- **Magnetic field saturation.** Longitudinal variation of the dipole field due to field leaking into the structural plate was verified both by magnetic measurements and FE models (Fig. 7). The air-gap between the yoke and the structural plates, which varied depending on the distance from the bolts, was determined to be the reason for this field variation. This led to blanch-grinding of the structural plates for a more uniform surface contact between the plates and the yokes.

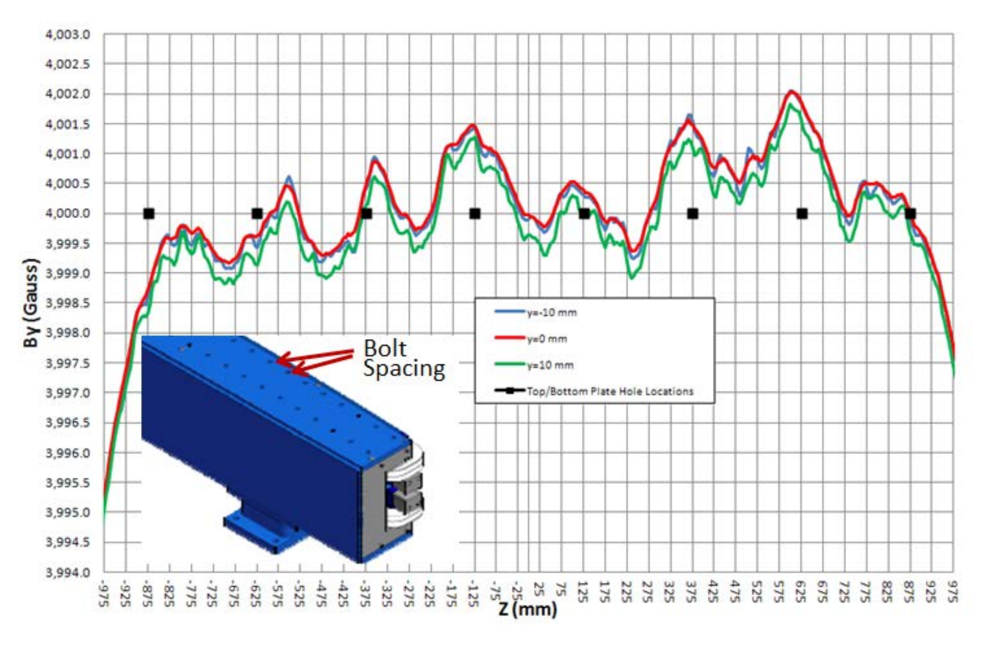


**Figure 7.** Longitudinal dipole field variation due to varying air gap between the dipole yoke and the structural plates.

- **Chamber supports.** The chamber supports were originally made from Invar-36 plates to improve thermal stability of the BPMs (beam position monitors) that are mounted on the chambers in line with the supports. Invar-36 has a low coefficient of thermal expansion (~ 1.2 µm/m°C), but it is also a magnetic material (permeability > 1000). Magnetic measurements showed that its proximity to the magnets adversely affected their field quality. The Invar-36 plates were subsequently replaced with carbon fiber composite plates with a comparably low coefficient of thermal expansion.

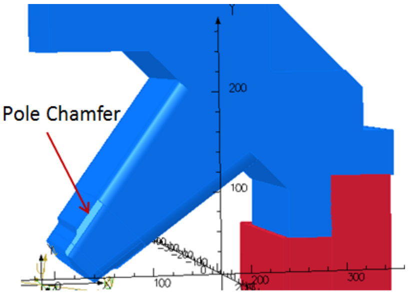


**Figure 8:** Pole chamfer to compensate machining error in a batch of quadrupoles.

- **Chamfering error.** A quadrupole supplier incorrectly chamfered a batch of 20 quadrupoles that drove one of the harmonics (b6) out of specification. From FE modeling and magnetic measurements, another pole chamfer (Fig. 8) was introduced to compensate for the machining error.

- **Cross-talk between magnets.** Magnetic measurements were performed to verify that the gaps between magnets were sufficient for an acceptable level of cross-talk.

- **Water temperature rise.** Unsymmetrical water temperature rise and its effect on the field quality was quantified.

The magnetic measurement capability became even more important when some discrepancies persisted between the suppliers' and BNL measurements. Also, approximately 80 received magnets needed re-shimming to bring their field harmonics within specifications. Although the initial BNL measurement plan was to verify only 10% of the magnet production, these issues led BNL to measure all magnets, many of them more than once. By the end of the project, three measurement benches were running simultaneously to keep up with the magnetic measurements, re-shimming, and finding various corrective measures.

## 9 Monitoring Progress

In addition to the project milestones such as design reviews, delivery of the first articles, and partial production, it is essential to monitor a supplier's progress by weekly conference calls and by frequent visits to the supplier's manufacturing facility.

A visit to the supplier's facility must be aimed at fully understanding his management structure, resources made available to the project, technical expertise of key personnel, and the capabilities of subcontractors. An important lesson-learned in this area was that the initial weekly conferences and visits relied too heavily on what the supplier conveyed rather than on detailed observations of what was occurring on the floor of the supplier's facility. In this regard, the initial couple of visits needed to be of longer durations than a few days, perhaps ~2 weeks. The longer duration would have allowed BNL not only to cover the items mentioned above, but also for rapport to develop between the supplier's and the BNL teams. It would have also allowed the BNL team from the start to provide concrete assistance in solving technical problems, in reviewing and editing their internal paperwork (e.g., design drawings and travelers), and in taking an inventory of materials at-hand and in procurement. In the case of one of the suppliers, BNL found it necessary to station a consultant full-time at the supplier's facility to assess the situation on a daily basis, to coordinate the work flow and to ensure the availability of the resources.

Another important lesson-learned was that some manufacturing issues were so technical in nature that their resolution was beyond the in-house expertise of the suppliers. In such cases, no useful purpose was served by issuing frequent reminders (by conference calls or short visits) to the suppliers about their contractual obligations. Once this was realized, the BNL team was expanded and reorganized to enable it to provide in-depth and timely technical assistance. The expanded team was able to respond to the manufacturers' enquiries in a timely manner, and time is money for the suppliers as well as for the project. Also, responding quickly conveyed to the suppliers our eagerness to stay on schedule.

The start of good rapport at the senior management level between the suppliers' and the BNL teams was a key factor in turning the magnet production around. The magnet suppliers were usually working on several projects simultaneously and often there was an intense competition for the available resources. The reallocation of resources at the supplier's facility usually required approval by its senior management. Such approvals were facilitated tremendously when the requests and proposals were made by the head of the BNL team who also held a senior position in the BNL directorate.

## 10 Assembly and Interferences

During the conceptual design phase the physics lattice was optimized to increase the lengths of the straight sections while ensuring adequate spacings between the multipole magnets for their assembly and alignment on the girders. At least 10 cm of gap was designed between the coils of any two adjacent magnets, and approximately 2 mm of gap between the chambers and the magnets' yokes and coils. Nevertheless, several assembly and interference issues arose, as described below. These issues could have been avoided with larger specified gaps and with more attention to 3D modeling and assembly processes.

## 10.1 Chamber Supports

The nominal gap of ~10 cm was not adequate for the chamber supports, especially for the flexible supports under the BPM assemblies (Fig. 9). The tight space was not convenient for assembling and adjusting the supports, installing alignment devices, and for making electrical connections to the lower BPM assemblies.

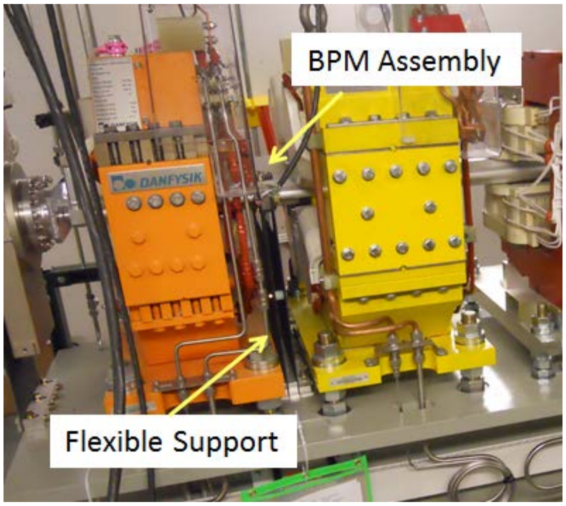


**Figure 9:** Tight space for the flexible chamber support and BPM assemblies.

## 10.2 Interferences between Magnet Poles and Chambers

The aluminum chambers were machined to create grooves for the magnet poles. This allowed magnet apertures to be small, thus reducing the cost of the magnets and their subsequent operational cost. A minimum transverse gap of 1.6 mm (Fig. 10a) was specified, which was barely sufficient, given the stack-up of various fabrication and assembly tolerances. For the NSLS-II magnets, a transverse gap of 2 mm would have been more appropriate.

A longitudinal (along the beam) gap of 10 mm was designed on both upstream and downstream ends of the magnet yokes (Fig. 10b). This gap turned out to be inadequate because some of the magnet yokes had been lengthened to avoid saturation, and some magnet nose pieces had to be longer for field matching. The longitudinal gap should be ~15 mm to allow for such modifications.

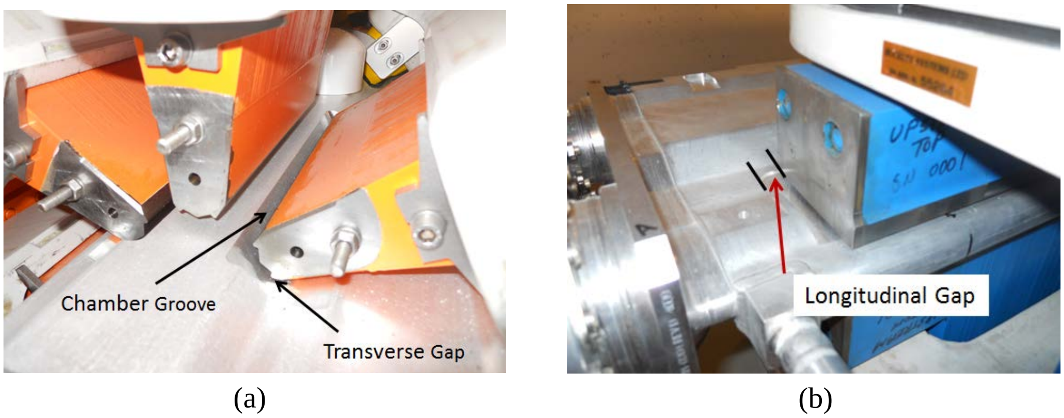


**Figure 10:** (a) Transverse gap between magnet pole and chamber groove; (b) longitudinal gap.

## 10.3 Interferences between Magnet Coils and Chambers

A minimum gap of 2 mm was specified between the magnet coils and the chambers. As mentioned in Section 6.6, this gap size turned out to be too small for a number of reasons: 1) the external dimensions of the epoxy-potted coils can vary by more than 1 mm, 2) coils can sag and shift during transportation, especially if the coil support brackets are not robust. Many coils were found to be touching the vacuum chambers when the magnets were inspected at BNL. No-go gage blocks (Fig. 11) mimicking the chamber shapes were provided to the suppliers to facilitate interference checks before the magnets were shipped. A number of coils (~ 20) were readjusted in their brackets at BNL, and in some cases the epoxy was slightly hand filed. In hindsight, a larger coil-to-chamber gap of 4 mm should have been specified.

**Figure 11:** Coil to chamber interference check with a no-go gage block.

## 10.4 Magnet Pole Clamps

Magnet pole clamps were include in the reference designs to stabilize the magnets during transportation and to improve field reproducibility after reassembly. One of the c-clamp designs (Fig. 12) was such that it was very difficult to reassemble the c-clamp after splitting the magnets and inserting the vacuum chamber.

A comprehensive set of magnetic measurements showed that the c-clamp was not beneficial to field reproducibility. The c-clamps of this design were subsequently removed from the magnets after their arrival at BNL.

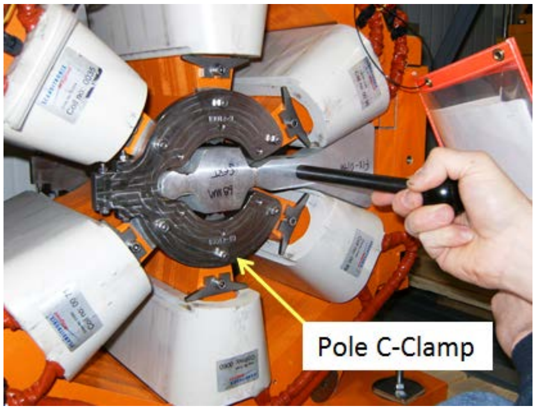


**Figure 12:** An assembled pole c-clamp for a sextupole magnet.

The c-clamps of another design were judged to be too weak to have any significant effect either during transportation or reassembly. The need for magnet pole clamps should be carefully investigated in future magnet designs.

## 10.5 Magnet Reassembly on Girders

To make girder–magnet assemblies, the selected magnets were first installed and pre-aligned on the girders. The magnets were then split at their mid-plane in order to install the vacuum chambers (Fig. 13a). Splitting of the magnets was not carefully considered during the design phase. This task turned out to be quite labor intensive. Detailed procedures had to be followed to avoid potential assembly errors and damage to the magnets. The unsupported water manifolds, water and electrical connections, and taped mating surfaces (as a measure against scratches and debris) can be seen in Fig. 13a. The amount of hardware that needed to be removed for splitting a single quadrupole is shown in Fig. 13b. In retrospect, ease of splitting and reassembly should have been a design criterion. The possibility of separate water manifolds for the upper and lower half of the magnets should be considered in the future designs.

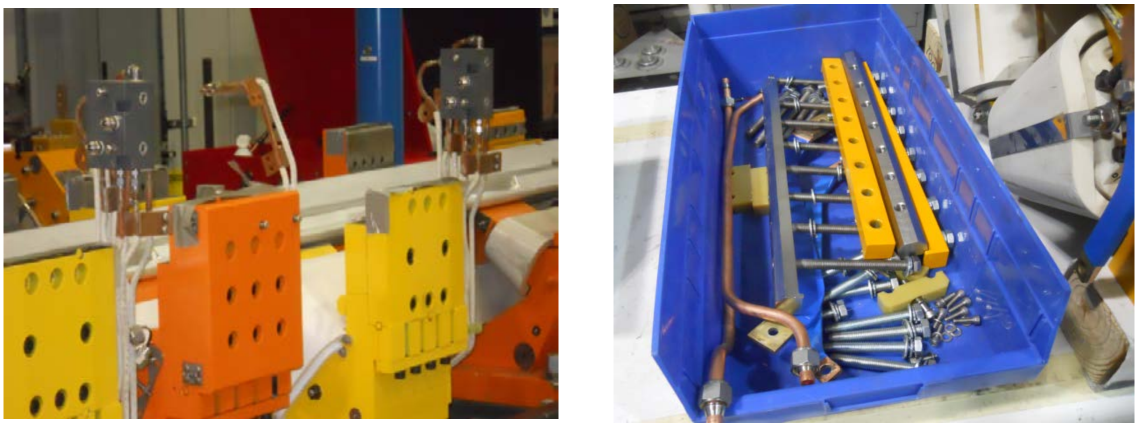

(a) (b)

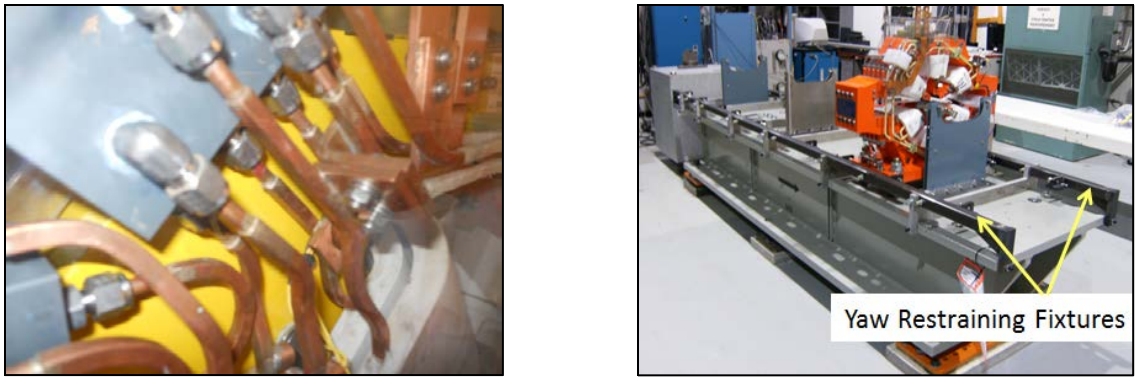
**Figure 13:** Splitting of the magnets. (a) Unsupported water manifolds, water and electrical connections, and taped mating surfaces. (b) Hardware removed from splitting a quadrupole.

## 10.6 Maintenance and Replacement

The assembly features of the magnets, utility connections, and alignment fixtures should be designed taking into account the ease of maintenance and quick replacement on a fully assembled girder.

Leaks at the water manifold connections have been a tenacious problem for the NSLS-II storage ring magnets. So far, approximately 20% of the water manifolds have been repaired for leaks. Water manifolds for the magnets were specified to be made from electrically-insulating plastics or ceramics. This material must have a right combination of strength, fracture toughness, ductility, and radiation resistance in order to provide long-term leak-tightness to threaded fittings. Although APS-type “ceramic” FEP was specified originally, different materials and sealants were later accepted.

The combinations of manifold material and sealant in two types of magnets were incorrect and have caused almost all of the leaks. The design of the manifolds (in both materials and configurations) should have been investigated in detail and defined precisely in the magnet specifications.



(a) (b)

**Figure 14:** (a) Water manifold with congested water connections and brazed joints.
(b) Yaw restraining fixtures that could not be used when replacing a magnet on a fully assembled girder.

Leaks also occurred, although much less frequently, at the brazed joints of the coils. Fig.14a shows an example of water connections and brazed joints that would be difficult to repair for leaks. Another cause of some infrequent leaks has been the combination of compression fittings with stainless steel ferrules on soft copper tubes.

Some of the plastic covers that shield electrical connections and water manifolds are too complex to be removed easily. This made the job of fixing leaks even more difficult. Another troublesome item was some suppliers' use of water fittings of different sizes. These fittings should have been standardized in the interface control drawings.

The yaw-prevention fixtures shown in Fig. 14b worked well for first assembly of the magnets, but could not be used in the tunnel to replace a magnet because of interference with the installed diagnostics hardware. A different fixturing had to be used when two sextupoles placed in the wrong locations had to be swapped.

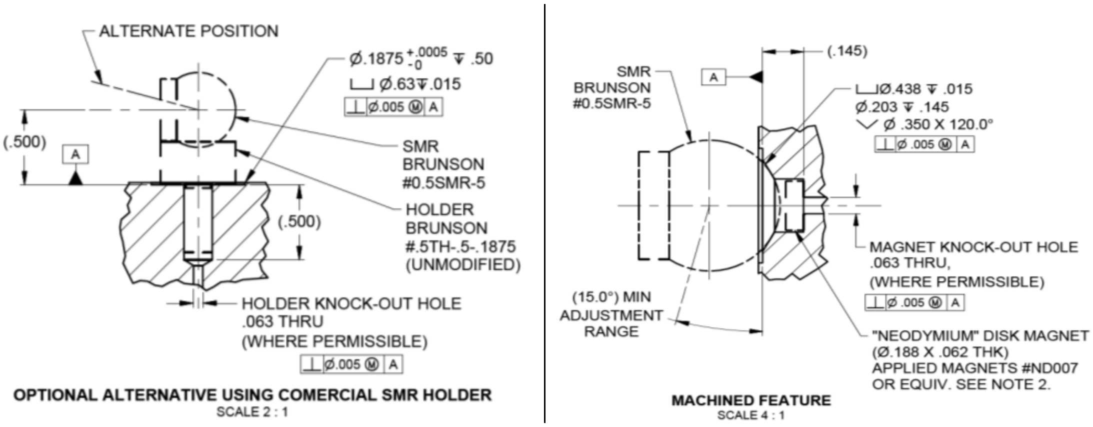
## 11 Magnet Alignment

The NSLS-II multipole magnets have been aligned to within the specification of ±30 µm. Based on experience gained in doing this high-precision alignment, it was realized that the process could have been made smoother by improving some alignment features of the magnets and by revisiting the alignment procedures.

### 11.1 Design of Survey Fiducials

Magnet survey fiducials can be holes, planes, or notches that are welded on, attached to, or machined on the magnet yokes. Their design is pivotal to the quality of survey and alignment. The NSLS-II magnet fiducials were deficient in the following respects:

- Reamed holes machined in the yokes were used as fiducials. Since a hole cannot be used directly as a reference, a pin-nest had to be used as an adaptor to realize the function of a fiducial, as shown in Fig. 15a. This had two major disadvantages, namely, poor repeatability (usually 20 µm, but as large as 50 µm), and a pin-nest that was hard to insert (or too loose). A preferable design is a conical feature welded on the magnet or a machined conical surface, as shown in Figure 15b.

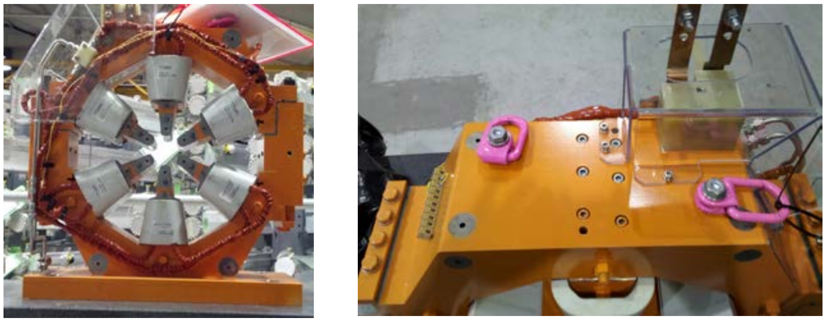


(a) (b)

**Figure 15:** Two types of magnet fiducials, (a) straight reamed hole in the yoke, (b) with conical feature.

- The magnet fiducials were not well distributed spatially. Due to interference with coils or protective covers, some fiducials were difficult to use. Fig. 16a shows an inaccessible fiducial inside the protective plastic cover. A fiducial with poor visibility is shown in Figure 16b.

**Figure 16:** Magnet fiducials. (a) fiducial inside the plastic cover; (b) poor visibility due to bus bar.



(a) (b)

- For the vibrating wire technique used to align the magnets precisely, the disadvantages mentioned above were not critical. However, if NSLS-II magnets had the preferred design of fiducials, the significant benefits would have been as follows:
    - Improved repeatability and reliability during the initial mechanical survey of the magnets and their pre-alignment on the girders.
    - A more reliable estimate of how well the magnets can be aligned using only fiducials, mechanical features, and laser trackers.
    - Improved efficiency and accuracy for future magnet repair or replacement. A recent swap of first sextupoles of girders C30G4 and C01G4 demonstrated the disadvantage of the present fiducials. Additional nests had to be glued on the target and the adjacent magnets and a full survey had to be performed to get a better reading of the relative magnet locations.

### 11.2 Precise Alignment without Vibrating Wire

The multipole magnets were assembled on their girders and rough aligned to ~ ±100 µm using laser trackers. The magnets were then split to install the vacuum chambers. After reassembly of the magnets, the girders were brought into the temperature-controlled (< ±0.1ºC) room where the magnets were aligned precisely by the vibrating wire technique.

Post analysis of all magnet alignment data shows that the magnets were aligned within 6 µm (rms) in the temperature-controlled room. Once the girders were transported to the tunnel, it was assumed that the potential non-repeatable gravity deflection and creep of the girders would introduce alignment errors. Therefore, the top surfaces of the girders were profiled in the temperature-controlled room and the profiles were re-established in the tunnel once the temperature around the girders achieved similar temperature stability. By the end of September 2013, the profiles of about half of the 90 multipole girders were re-established. On average, it took about 4 hours per girder to re-establish the profile. The profiling error on these girders was ~5 µm (rms) after averaging out systematic errors that do not affect relative alignment of the magnets. Adding the alignment errors in quadrature, the data show that the NSLS-II magnets have been aligned to an unprecedented accuracy of 8 µm (rms), well within the specification of ±30 µm.

The data also showed that the rough-aligned magnets were within ~40 µm (rms) of their final positions. This raised the possibility that magnet alignment specification of ±30 µm could be achieved using the traditional laser tracker method. While less accurate, the traditional method is less labor intensive and puts less constraint on the assembly sequences. As a simulation to test the alignment precision achievable by laser trackers, one quadrupole on the last production girder, C19G4, was intentionally left out of alignment by (0.066, 0.125) mm. Then laser trackers were used to align this quadrupole into the best fit magnetic center line. After multiple alignment steps, laser tracker-based alignment produced a final offset of (0.002, 0.009) mm. Comparing this with the offset of (-0.001, 0.012) mm from the vibrating wire technique: the deviation between two systems was only (-0.003, 0.003) mm.

Aligning the magnets to ±30 µm using only laser trackers would include the following steps:

- Establish magnetic axis of each magnet precisely (e.g., by the vibrating wire method in a temperature-controlled room) and transfer it to the magnet fiducials to within ±10 to 15 µm precision. Whether this level of precision can be achieved using only the mechanical axes of the magnets, and in a normal lab environment, needs further investigation.
- Pre-align the magnets on a girder in a normal temperature environment with ~100 µm precision.
- Align the magnets in the temperature-stabilized (±0.1ºC) tunnel with ±10~15 µm precision.

## 12 Transportation Issues

Under the “General Terms and Conditions” of the contract, magnets that did not meet specifications or that were damaged during shipping could be returned to the supplier at his expense. In practice, however, returning the magnets can be quite disruptive to the magnet acceptance and girder assembly schedules. The shipping issues can be avoided by taking appropriate measures in advance, as described below.

1. All suppliers received pre-shipment checklists tabulating all tests and measurements that they needed to perform to ensure that shipped magnets met all specifications. The checklists were reviewed and approved by members of the Magnet Acceptance Committee before the magnets were authorized for

shipment. This procedure also turned out to be quite useful in the handling of minor variances from the specifications.

2. Although the packaging requirements were specified in detail in Section 3.13 of the SOW, some magnet suppliers did not meet these requirements adequately with regard to the thickness of the plywood, design of the base, attachment of the magnets to the base, and moisture control. The suppliers were asked to redesign the crates and the magnet-attachment details. The design of the shipping crates should have been reviewed in detail during the FDR (Final Design Review).
3. The suppliers were advised to use trucks rather than freight trains for over-land shipment in order to avoid lateral shocks to the magnets during shunting of the freight cars.
4. The shock and temperature sensors were attached to the exterior of all crates, but their performance and reliability were not consistent. The particular brands of sensors should have been specified to the magnet suppliers.
5. The shipments of magnets from various suppliers were tracked on a daily basis to facilitate advanced preparation for their off-loading and to schedule acceptance tests.

## 13 Construction Spare Magnets

The magnet assembly and installation schedules during the final few months benefitted from the availability of construction spares of several types of multipole magnets. Although the construction spares were not included as part of the original magnet contracts, they became available for two main reasons. When a contractual change was made due to a change in the physics lattice and the count of standard aperture sextupoles was reduced, 3 sextupoles were retained as construction spares. The magnet back-up suppliers program led to 6 large-aperture sextupoles, 4 large-aperture quadrupoles, 3 double-coil short quads, and 4 double-coil wide quads. The construction spares were important in addressing the following issues during the final few months:

- A magnet that had been formally accepted was damaged during in-house assembly and installation; it could be sent back to the supplier for repairs.
- A few of the magnets were severely damaged during shipping. These were sent back to the suppliers for repair.
- Several magnets had field qualities just outside specifications. They were set aside for re-shimming at a later date without disrupting the magnet assembly schedule.
- Some magnets were delayed because the supplier unexpectedly ran out of assembly hardware.

Advantages that can be realized by ordering construction spares with the original contract include receiving production pricing for the construction spares due to economies of scale gained from producing the spares along with the production run, and ensuring that the magnetic material properties for both the spares and the production magnets are the same as a result of processing the laminations from the same batch of steel. It would be a good practice to include construction spares in the original contracts, a practice which is widely allowed in construction projects. If construction spares are not used, they are transferred to the special process spares' account upon completion of the project.

## 14 Magnet Database and Travelers

The SR magnet procurement has generated an extensive quantity of documents, drawings, and datasets, partly due to the large number of magnets of different types and from different suppliers. These included: magnet specifications, procurement documents, BNL reference CAD models and drawings, design review reports, trip reports and meeting notes, suppliers' CAD models and drawings, design variation documents, suppliers' magnetic measurements data, suppliers' manufacturing travelers and material certifications, discrepancy reports, shipping documents, BNL magnetic measurements data, BNL magnet survey data, test procedures, BNL magnet travelers, magnet acceptance documents, and magnet pre-alignment and precision alignment data. There were also numerous internal and external presentations, reports and papers.

As a contractual requirement, NSLS-II had received all suppliers' CAD models and drawings in Autodesk Inventor format. These were easily integrated in our girder assembly models and stored in the Autodesk Vault database. A BNL online discrepancy reporting (DR) system with searchable database was also used successfully. It was envisioned that other documents and datasets would become a part of a large database that was being developed for the purpose of storing relevant information for all accelerator systems. This database would have also allowed real-time entry of magnet data (magnetic field, survey, mechanical and electrical tests) remotely on user-friendly screens.

For various reasons, however, this database was still under development when the production magnets started arriving at BNL. Lack of time prevented the evaluation and selection of an alternate database. This led to magnet documents and datasets being stored in various places and formats. Magnet travelers and test data, for instance, were recorded manually on paper sheets, which were then scanned and their data manually entered in Excel tables. Relevant magnet data for commissioning (field harmonics versus current, magnetic lengths, alignment data) were compiled by a physicist in a separate database. While all magnet data are now accessible electronically, the effort required in manual duplication has been considerable. In retrospect, the possibility of the database under development not being ready in time should have been considered in advance and a backup plan should have been prepared.

Appendix 1

## Magnet Production Workshop

April 11– 12, 2012
Brookhaven National Laboratory
Upton, NY 11786, U.S.A.

***List of Participants***

| | |
|---|---|
| C.H. Chang | Taiwan Photon Source |
| Frank DePaola | Brookhaven National Laboratory |
| Tom Dilgen | Brookhaven National Laboratory |
| Lewis Doom | Brookhaven National Laboratory |
| John Escallier | Brookhaven National Laboratory |
| Weiming Guo | Brookhaven National Laboratory |
| Hsiao-chaun Hseuh | Brookhaven National Laboratory |
| Mark Jaski | Argonne National Laboratory |
| Animesh Jain | Brookhaven National Laboratory |
| Erica Kazantseva | Budkar Institute of Nuclear Physics |
| Sam Krinsky | Brookhaven National Laboratory |
| Satoshi Ozaki | Brookhaven National Laboratory |
| Chris Philpott | Buckley Systems LTD. |
| Tatyana Rubitskaya | Budkar Institute of Nuclear Physics |
| Steve Seiler | Brookhaven National Laboratory |
| Sushil Sharma | Brookhaven National Laboratory |
| Serguei Sidorov | Paul Scherrer Institute |
| Charles Spataro | Brookhaven National Laboratory |
| Alexandr Starostenko | Budkar Institute of Nuclear Physics |
| Aleksandr Tsyganov | Budkar Institute of Nuclear Physics |
| Ferdinand Willeke | Brookhaven National Laboratory |

Presentations at the Workshop can be found at the BNL website below:
[http://www.bnl.gov/nsls2/workshops/docs/041212_Magnet_Workshop/default.asp](http://www.bnl.gov/nsls2/workshops/docs/041212_Magnet_Workshop/default.asp)

### Appendix 2

## Field Qualities of NSLS-II Multipole Magnets

Author: Weiming Guo

The measured field harmonics of the NSLS-II multipole magnets are shown below in Figures A and B. The field harmonics are defined as:

$$A_{n+1} = \frac{a_m r^m}{b_n r^n} \text{ and } B_{n+1} = \frac{b_m r^m}{b_n r^n}$$

where r = 25 mm is the reference radius.

$$a_n = \frac{1}{n!}\frac{\partial^n}{\partial x^n}B_x \text{ and } b_n = \frac{1}{n!}\frac{\partial^n}{\partial x^n}B_y .$$

The denominator is for the main field, n=1 for a quadrupole and n=2 for sextupoles. These harmonics represent the pure field strength of a 2(n+1)-pole magnet.

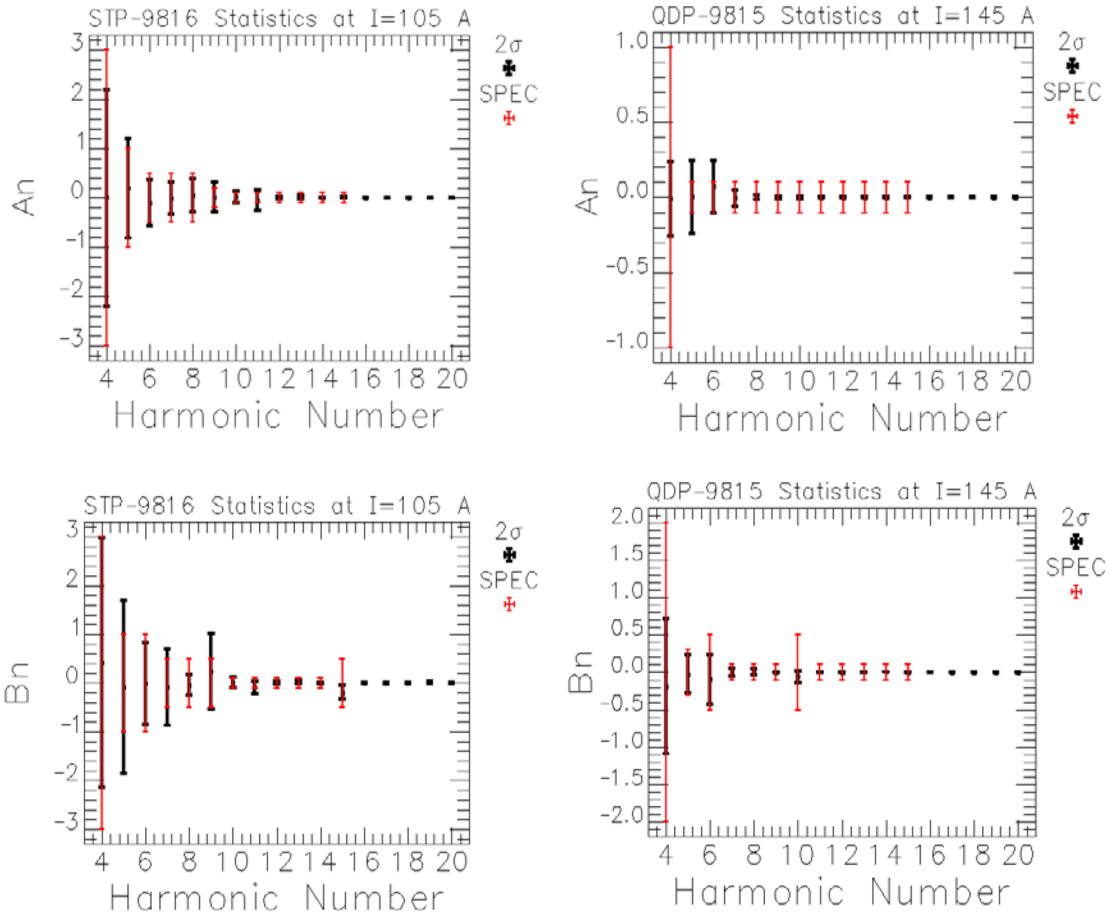


**Figure A:** (Left) Measured 2σ values (black bars) versus maximum specifications (red bars) of the field harmonics for the standard aperture (66 mm) sextupoles. (Right) Comparisons for the standard aperture (66 mm) quadrupoles.

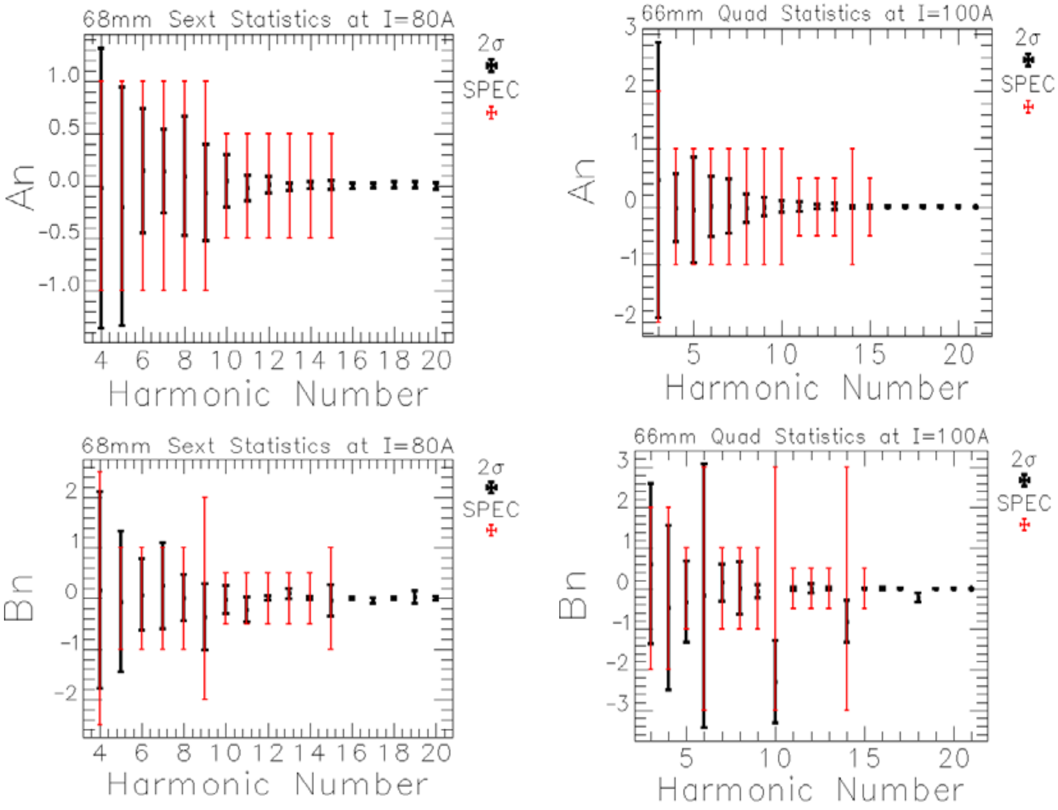


**Figure B**: (Left) Measured 2σ values (black bars) versus maximum specifications (red bars) of the field harmonics for the large aperture (76 mm) sextupoles. (Right) Comparisons for the standard aperture (90 mm) quadrupoles.

As shown in the figures, most magnets met the field specifications. Some of the magnets had only one or two harmonics that were out of specifications. They were accepted by the Magnet Acceptance Committee after beam dynamics considerations.

The figures show only the BNL measurement data. The magnets were also measured by the suppliers at their facilities, but small discrepancies persisted between the suppliers and the BNL measurements. In addition, about 10% of the magnets were re-tuned at BNL following initial measurements or after reassembly tests