Storage Ring Magnet Production for NSLS-II

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Acknowledgment

Collaborators:

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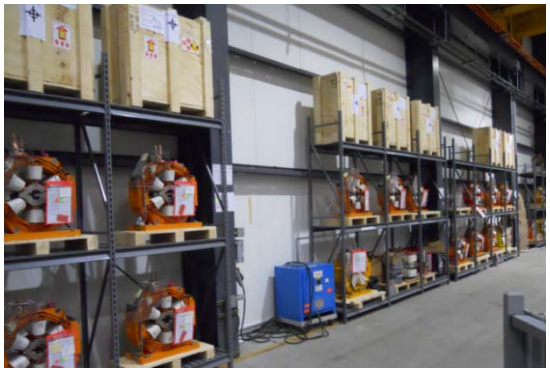
Outline

- Introduction - Lattice and magnet types
- Specifications and Tolerances
- Yoke Machining
- Yoke Bonding Issues
- Re-assembly Issues
- Magnet Transportation
- Summary

NSLS-II SR Magnets Program

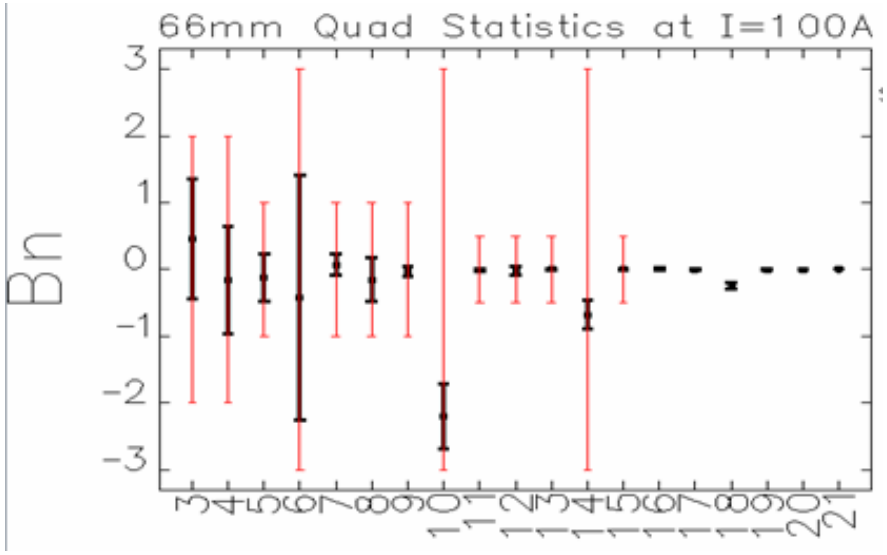


Magnets Inventory

Girder Assembly

Girder Installation

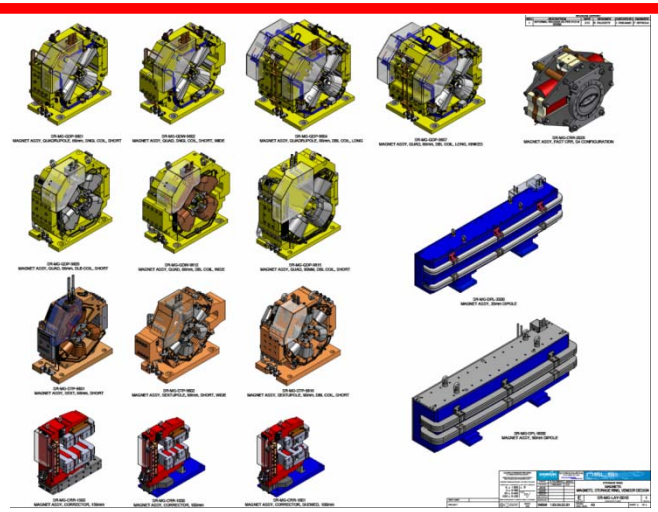
- All magnets have been shipped. ~ 99% received and ~ 80% measured.
- The magnets meet stringent field specs. of NSLS-II, making them among the best magnets ever built.
- Advances were made in magnet manufacturing.
- The magnets will be installed in the ring ~ 8 months before the start of commissioning,



Red – Range allowed
Black – Range measured

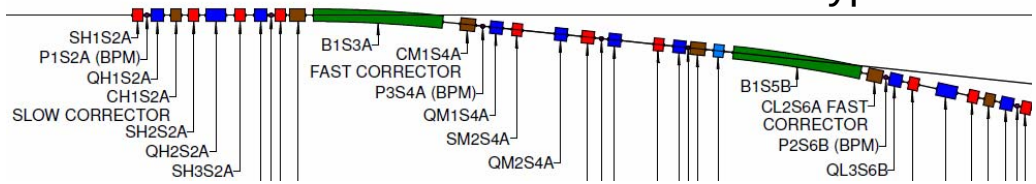
SR Magnets

- The SR magnets consist of 7 types of quadrupoles, 3 types of sextupoles, 2 types of dipoles and 4 types of correctors.
- 825 magnets out of 842 have been received. All magnets were built precisely to meet the stringent field specifications of NSLS-II.



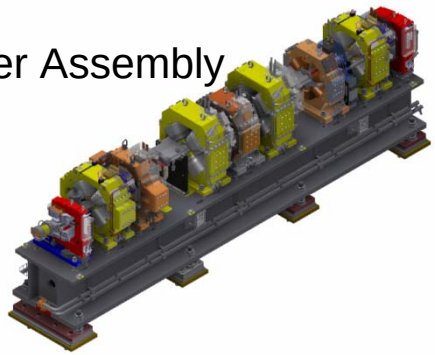
Magnet Type	Number	Suppliers
Dipoles	60	BSL (New Zealand)
Quadrupoles	300	BINP (Russia), Tesla (England), BSL (New Zealand)
Sextupoles	270	Danfysik (Denmark), IHEP (China), BSL (New Zealand)
Correctors (slow)	180	Everson (USA)
Correctors (fast)	90	Sag Harbor (USA)

Magnet Types and Suppliers



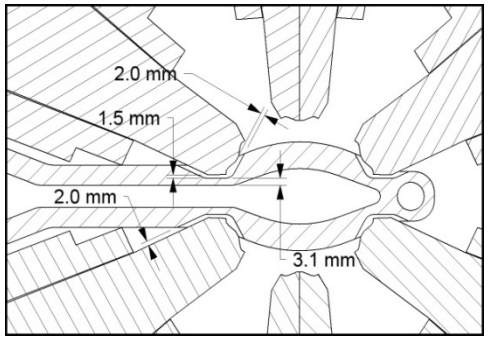
NSLS-II Lattice

Typical Girder Assembly



Girder

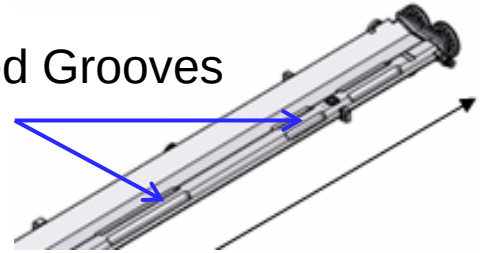
BPM Stand



Chamber Gap

- A tight lattice required magnets of different lengths.
- Parallel designs and close interface tolerances required the magnet reference designs to be fully developed.
- As the reference designs were developed they were released for procurement.

Machined Grooves



NSLS-II Magnet Specifications

Harmonic No.	Original Specs.		Revised Specs.	
	Norm.	Skew	Norm.	Skew
3	2.0	2.0	2.0	2.0
4	2.0	1.0	2.0	1.0
5	1.0	1.0	1.0	1.0
6	1.0	0.5	3.0	1.0
7-8	0.5	0.5	1.0	1.0
9	0.1	0.1	1.0	1.0
10	3.0	0.1	3.0	1.0
14	2.0	0.1	3.0	0.1
11-13, 15	0.1	0.1	0.5	0.5

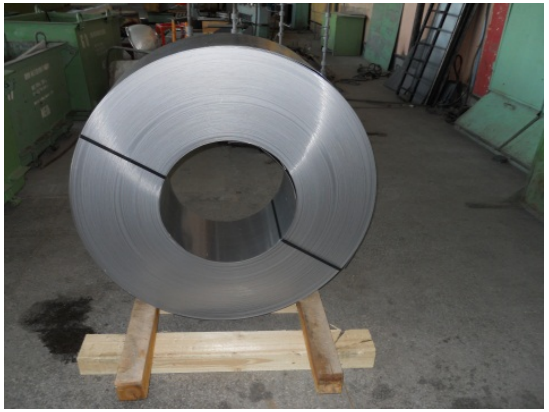
The original specs could not be met.

Even the revised magnet specifications were too tight to be met by normal magnet manufacturing methods.

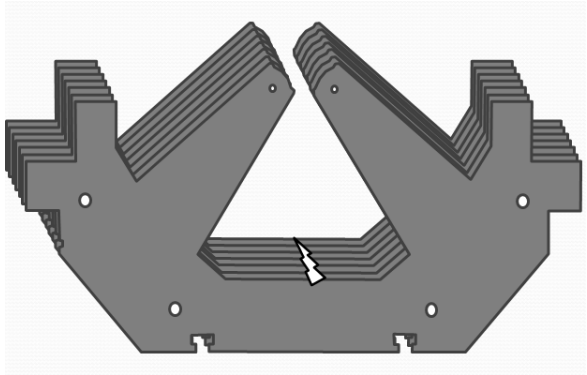
Reassembly Spec: The changes in harmonics are to be within 20% of their allowed value.

Specifications for NSLS-II Quadrupole (66-mm Aperture)

Magnet Manufacturing - 1



Roll of Magnet Steel

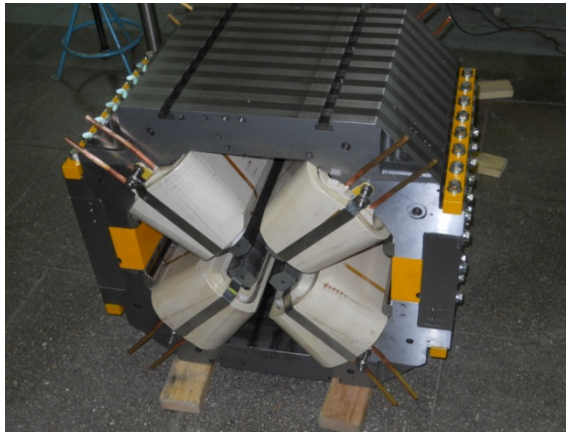


Laminations

Stacking

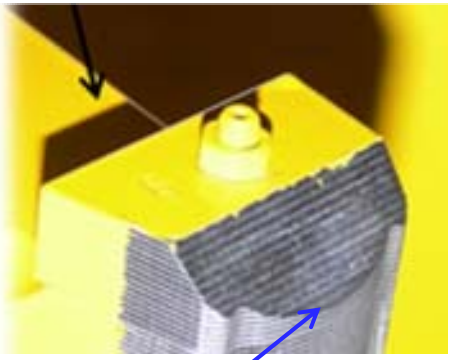
Curing Oven

Dimensional Check

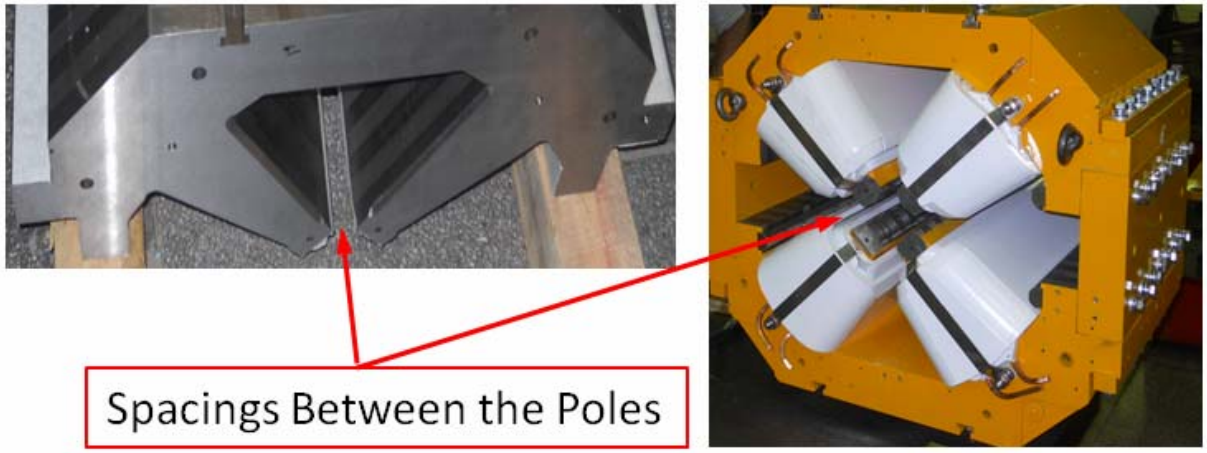


Magnet Assembly

Tolerances



Pole Profile



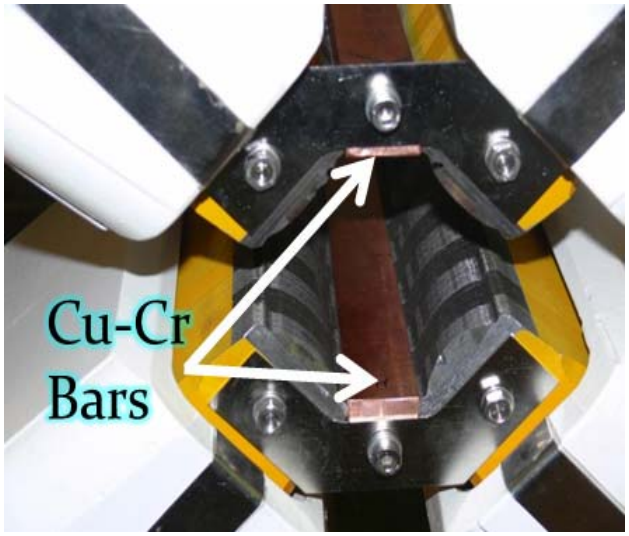
Tolerances Necessary to Achieve NSLS-II Specification:

- Pole Profile: ~ 10 µm (can be achieved by fine blanking)
- Pole Spacings: ~ 15 µm
- Top-Bottom Asymmetry: 0.5%
- Magnet Re-assembly: < 5µm

Precision Machining

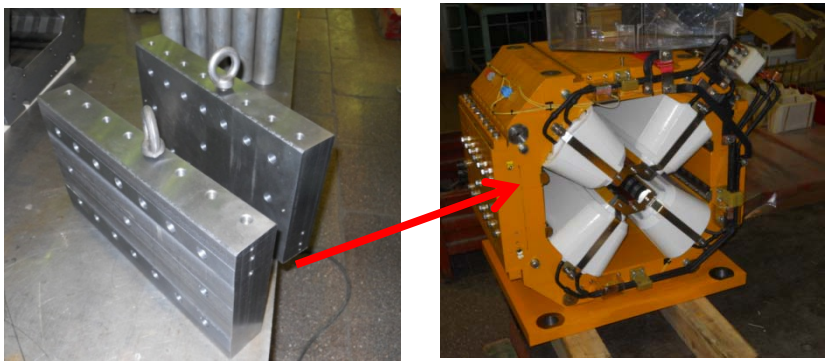
Wire EDM

CNC -Milling



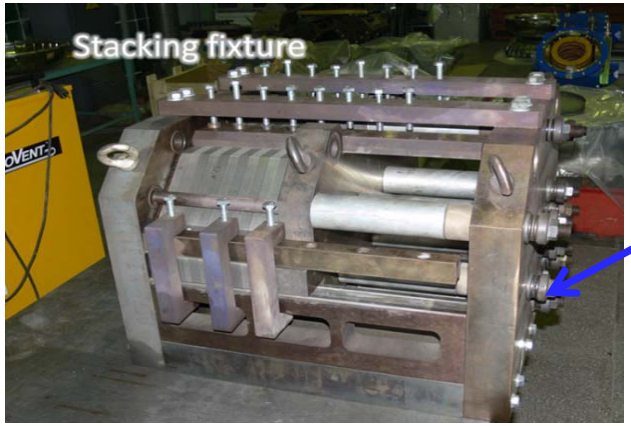
Precision-Ground Spacers

- Wire EDM
- CNC – Milling
- Grinding of Spacers
- Almost all suppliers had a long learning curve in mastering the details.



Precision-machined Spacers

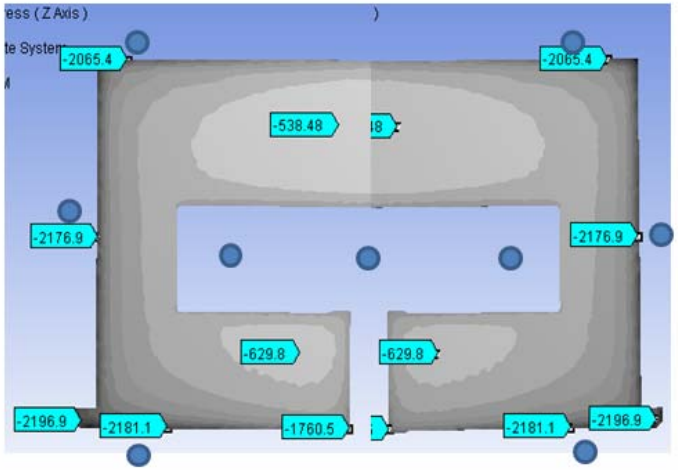
Stacking Fixture and Bonding Issues - 1



Belleville Washers

Stacking Fixture with Tie Rods

FE Analyses – Pressure in psi



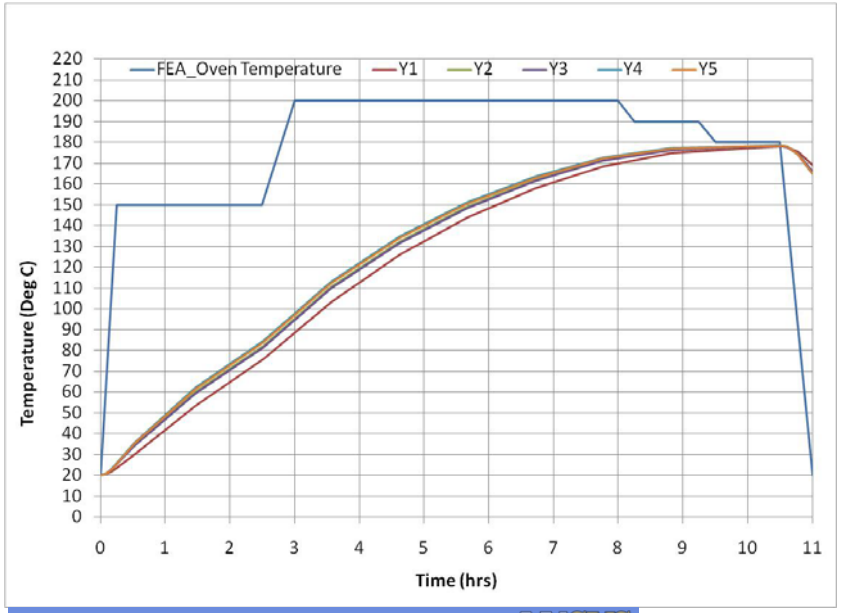
Equal Tension on 9 Tie Rods (●)

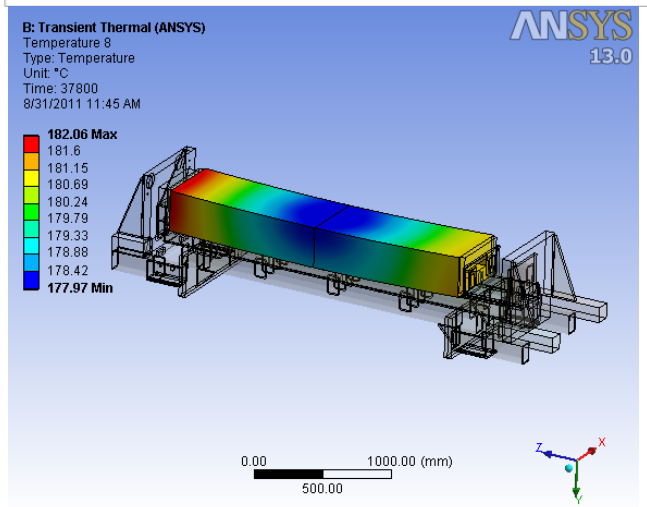
Tension in Central Rods = 3 x Outer Rods

- Stacking fixture should be able to apply uniform pressure (3 – 6 MPa) on the stack of laminations. 3 MPa is the recommended pressure, but a higher pressure results in better pressure uniformity.
- The stacking fixture without tie rods allows more flexibility in distributing the pressure.
- The stack should be compressed after each bundle of ~ 200 mm of laminations.

Stacking Fixture and Bonding Issues - 2

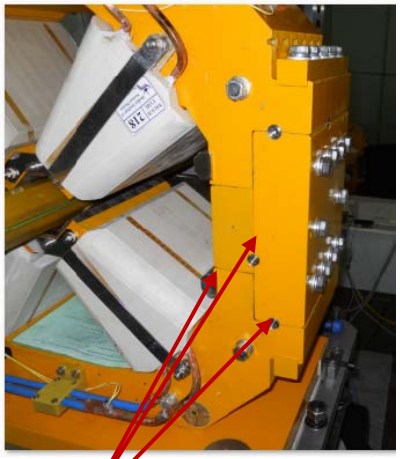
- Stack shrinkage (~ 5 mm/m) in oven due to compression and oozing out of the epoxy coating (~ 7 μm thick). The Belleville washers stacks should be designed to take this shrinkage into account .
- For epoxy curing, ThyssenKrupp recommends a soak time of 2 hours at **160° C, or 1 hour at 180° C.** A thermal analysis is recommended to establish the expected temperature profile in the yoke.



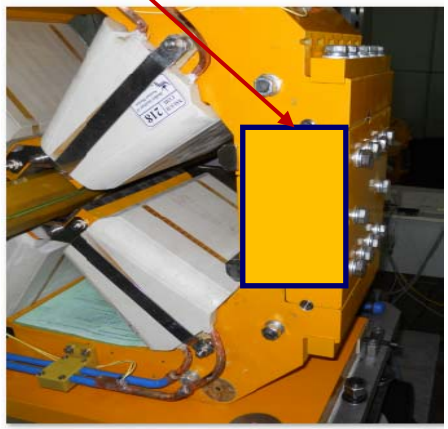


Dipole Stack - Thermal Analysis

Magnet Re-assembly



Mating Surfaces



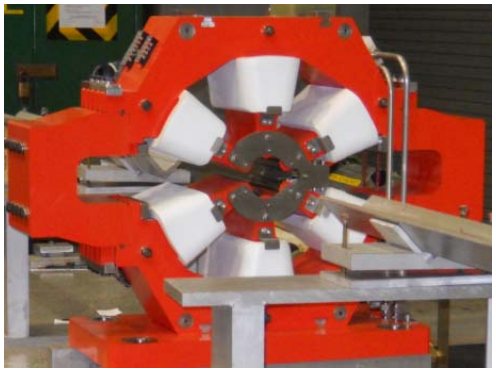
Preferred - Spacer Block

- The magnets must be split and re-assembled in order to install vacuum chambers.
- The original specifications (re-assembly within 5 μ m) was not verifiable in production.
- The specification was changed to: changes in harmonics < 20% of their allowed values.
- All vendors had problems with meeting the re-assembly specification.

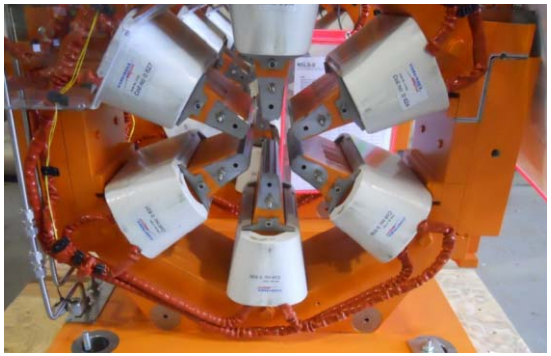
- Avoid bending deformations and frictional sliding. The spacer blocks should be under compression.
- Avoid multiple mating surfaces.
- Use only vertical bolts.
- Mating surfaces should be machined precisely.

Magnet Re-assembly -3

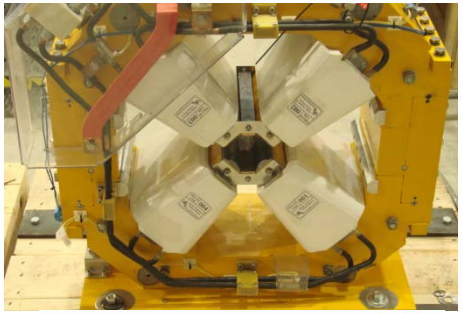
NSLS-II Wide Sextupole

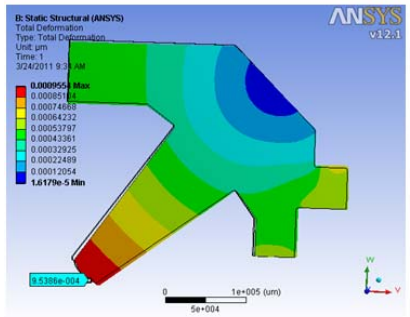


NSLS-II Normal Sextupole

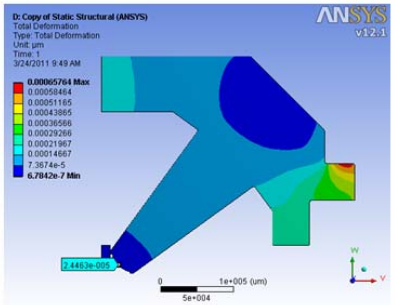


NSLS-II Quadrupole (BINP)





ΔD = 1 nm



ΔD ~ 0.02 nm

Reduction Factor: ~40

- Magnets should be structurally robust to insure reproducibility of the magnetic field.
- C-clamps were removed from NSLS-II normal sextupoles – they adversely affected the repeatability.
- FE analyses showed that the spacer bars can significantly stiffen the magnets, thus improving reproducibility.

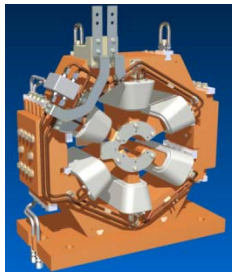
Magnet Re-assembly - 2

Bolting Sequence and Specifications:

- NSLS-II magnets experience higher deformations under a horizontal force than a vertical force.
- By keeping horizontal force one-half the vertical force, the probability of horizontal sliding is reduced.

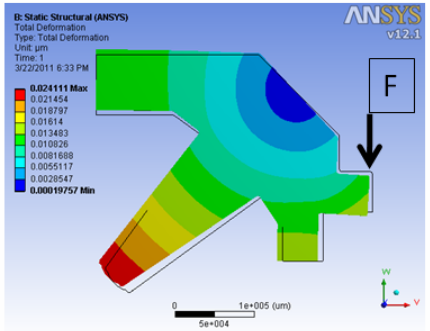
Recommended Bolt Torques (NSLS-II):
Vertical: 50-60 N.m
Horizontal: 25-30 N.m
Anti-seize lubricant such as Kema RG-100

Design the interface without horizontal bolts !



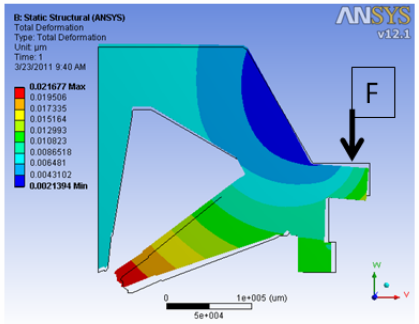
FE Analyses: by V. Ravindranath

NSLS-II Quadrupole

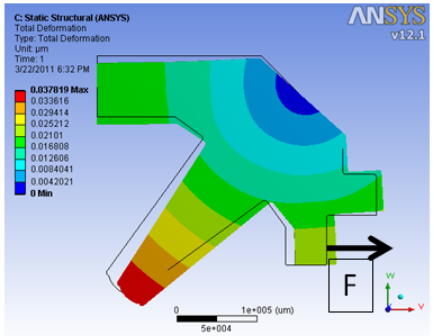


Dmax = 24 nm

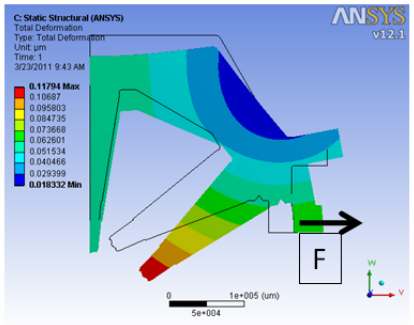
NSLS-II Sextupole



Dmax = 22 nm



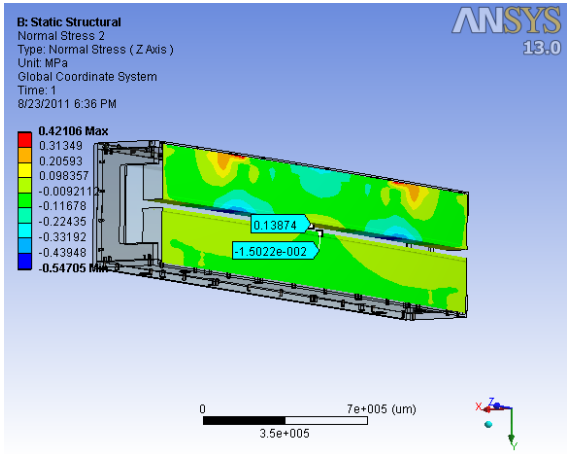
Dmax = 38 nm



Dmax = 118 nm

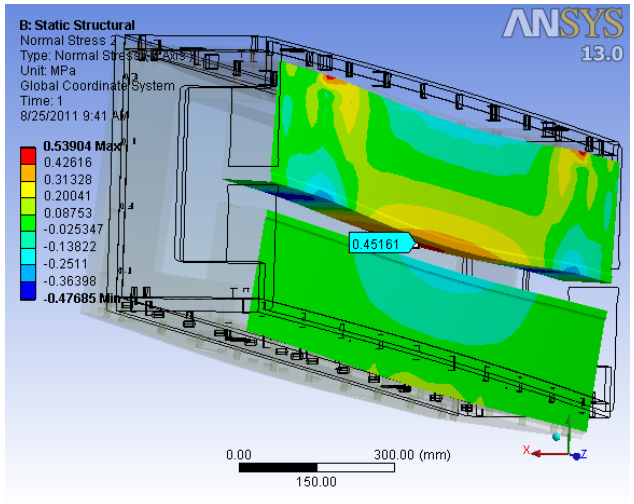
Lifting and Transportation - 1

S_{max} = 0.14 MPa



Lifting from Top Lugs

S_{max} = 0.46 MPa



Lifting from Bottom Lugs

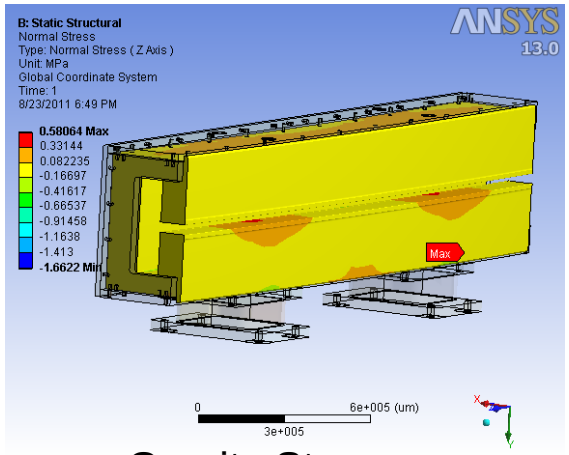
FE Analyses: by V. Ravindranath

- Lifting the magnets from top lugs produced less stresses than the less-optimally placed bottom lugs.
- Bottom lugs were subsequently removed.

Lifting and Transportation - 2

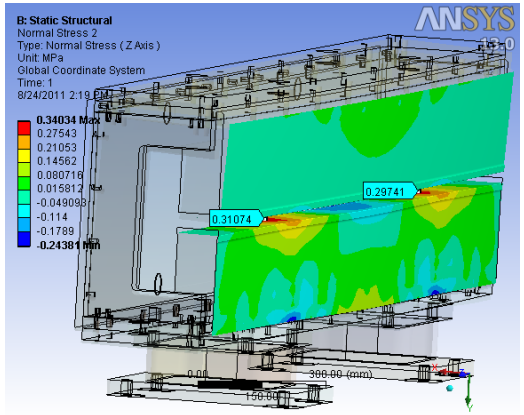
FE Analyses: by V. Ravindranath

S_{max} = 0.36 MPa

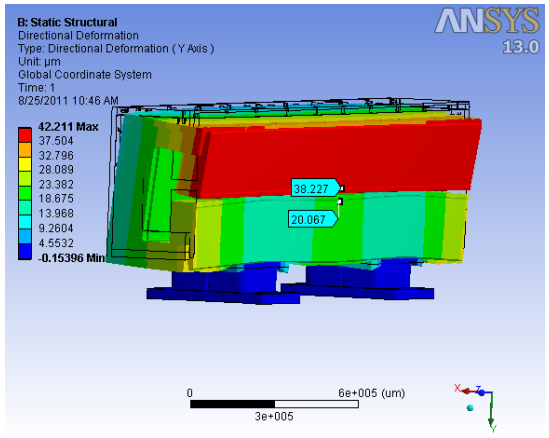


Gravity Stresses

S_{max} = 0.34 MPa



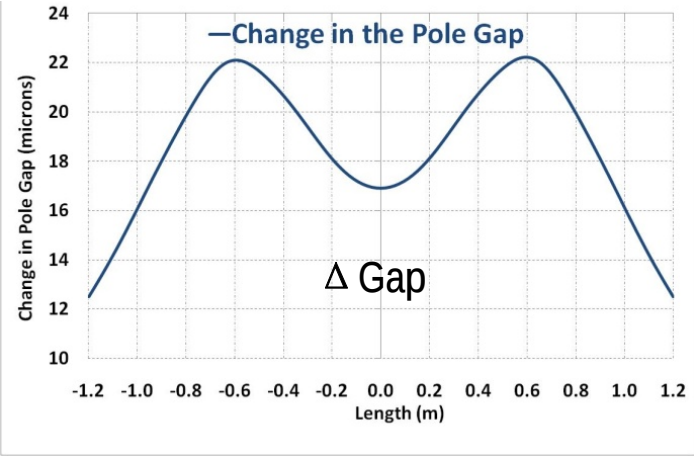
Additional Plates – 27 mm Thick



Gravity Deformations

Micro-fissures were discovered in the yokes of the 35 mm dipoles.

- Under its self-weight the maximum normal tensile stress (S_{max}) = 0.36 Mpa.
- Adding extra top and bottom plates were not effective.
- The magnet feet are removed during transportation.
- The maximum change in the pole gap, ~ 10 µ m.



Team Work

BINP Director's Office

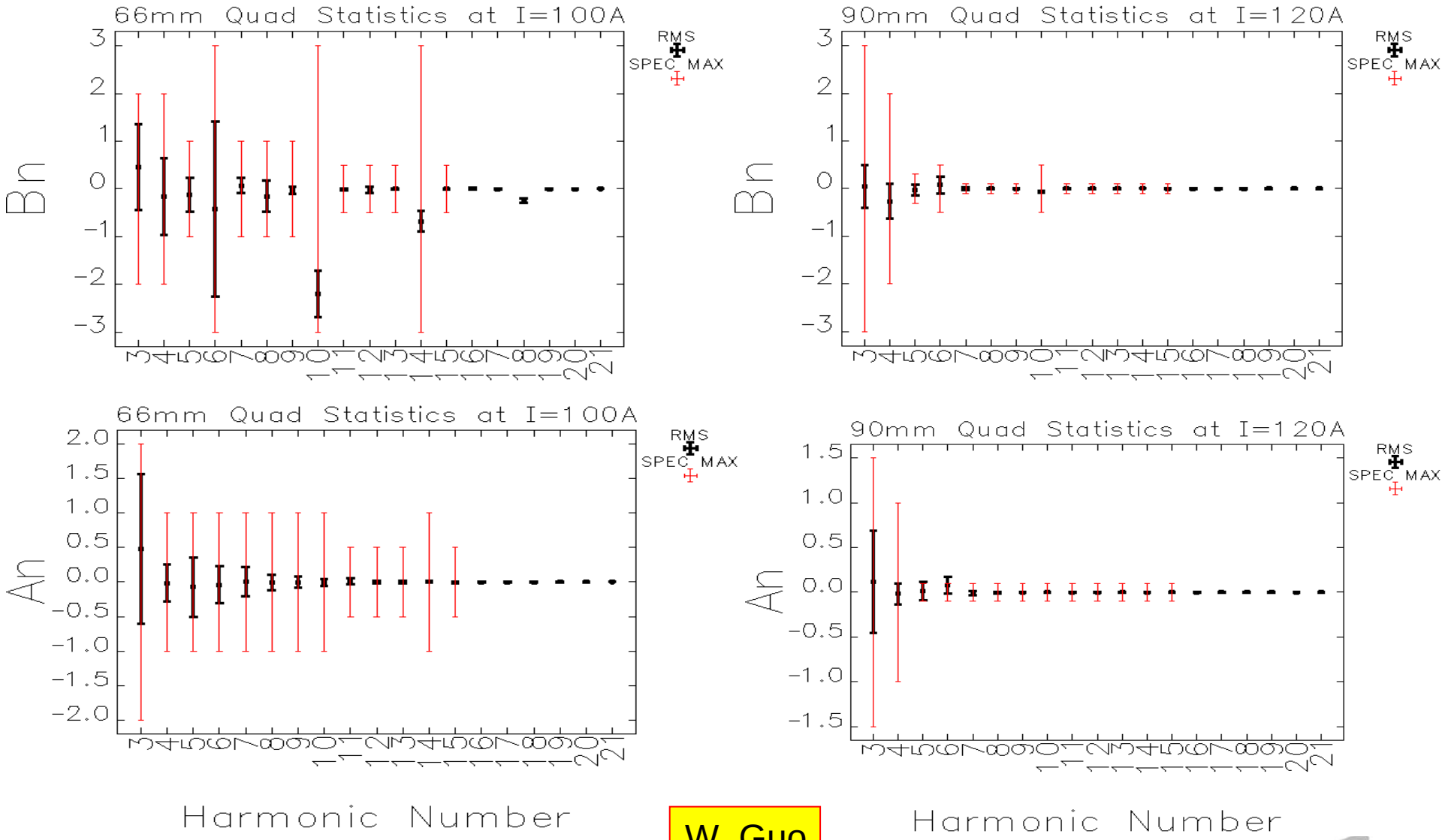
Dipole Yoke at BSL

EDM Subcontractor

- Daily communication with the suppliers.
- Commitment of the supplier's management.
- Solving problems as a team.
- Flexibility and compromise.

Meeting at BINP Workshop

Statistics of Quadrupoles



W. Guo

Summary

- The production of NSLS-II SR magnets has been successfully completed.
- All magnets meet stringent field requirements.
- The magnets required high-precision machining and careful assembly techniques.
- Numerous technical and manufacturing problems were resolved in a close collaboration with the suppliers.
- The state-of-art of magnet manufacturing has been advanced.

A magnet workshop was held at NSLS-II on April 11-12, 2012 to discuss and document our experience on the SR magnets production. The presentations are available at:

http://www.bnl.gov/nsls2/workshops/docs/041212_Magnet_Workshop/default.asp