Special Magnet Designs and Requirements for National Synchrotron Light Source II (NSLS-II)

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For NSLS-II Magnet Team*

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*** + J. Skaritka, A. Jain, M. Rehak, C. Spataro**

Content of the Presentation

- ❑ Brief overview of NSLS-II storage ring and its magnets
- ❑ New developments in dipole design that significantly extend its magnetic length for the same mechanical length
- ❑ New developments in quadrupoles, sextupoles and corrector magnets
- ❑ Notable progress in magnetic measurement and alignment techniques

➢ **The focus of this presentation will be significant developments in magnet technology during the NSLS-II R&D program**

Acknowledgement

This presentation will give an overview of the work of NSLS-II magnet design and measurement team (other members: J. Skaritka, A. Jain, M. Rehak, C. Spataro) .

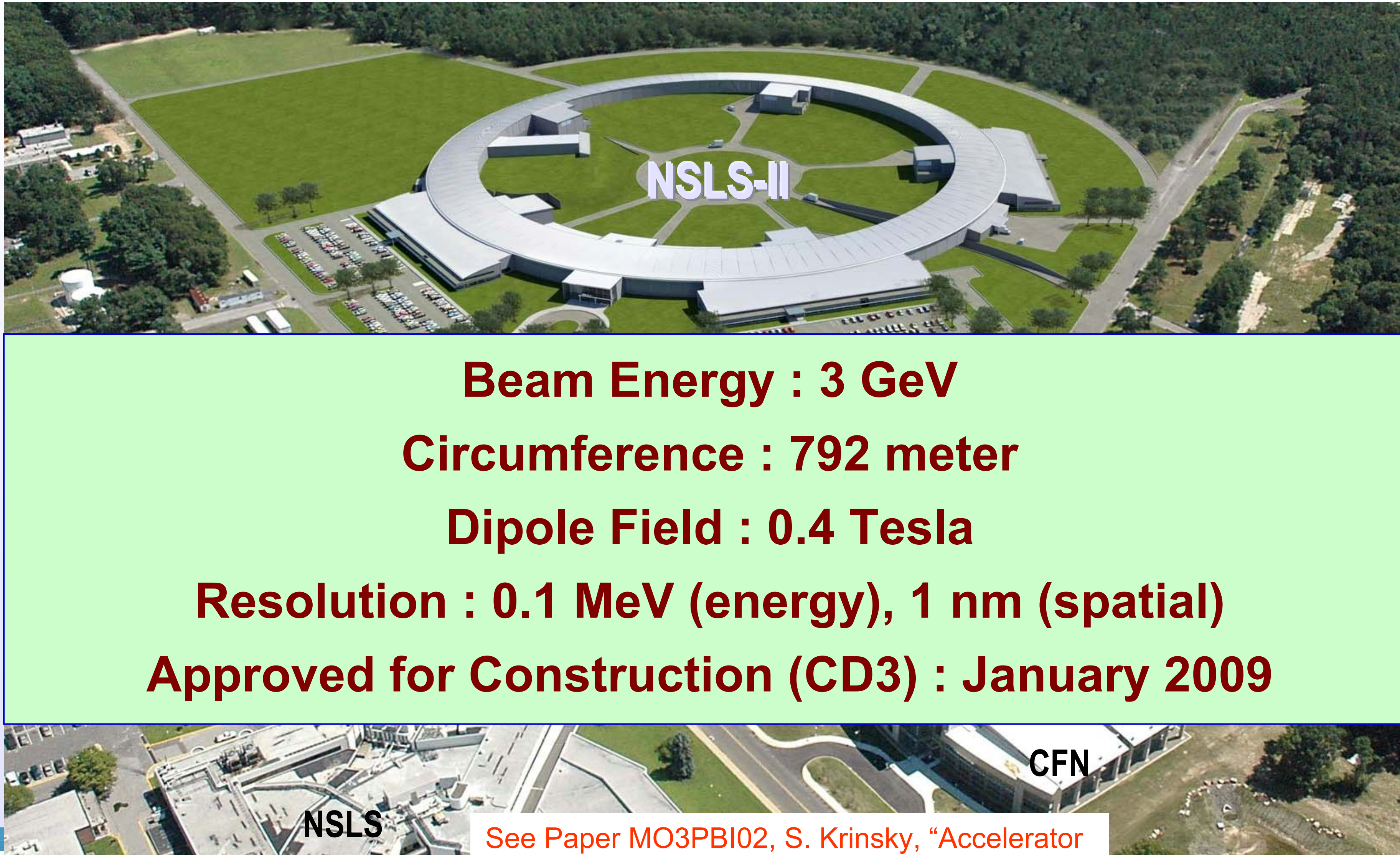
Important contributions and feedback from the following is also appreciated:

M. Anerella, J. Escallier, G. Ganetis, P. He,

P. Joshi, S. Krinsky, P. Kovach, S. Ozaki,

S. Plate, S. Sharma, P. Wanderer and F. Willeke

NSLS-II Storage Ring



Beam Energy : 3 GeV

Circumference : 792 meter

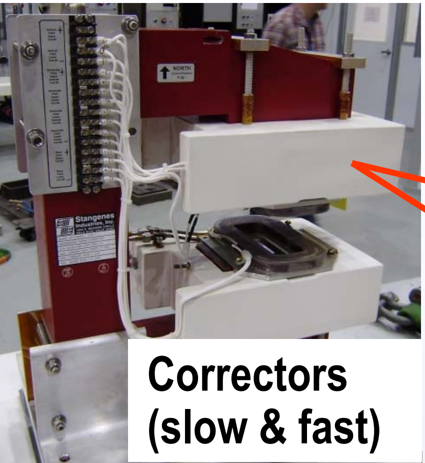
Dipole Field : 0.4 Tesla

Resolution : 0.1 MeV (energy), 1 nm (spatial)

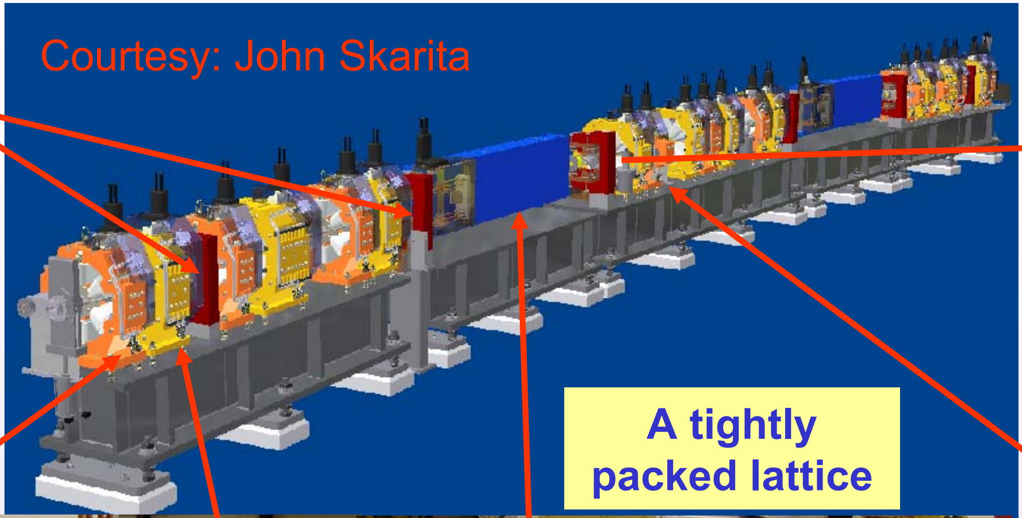
Approved for Construction (CD3) : January 2009

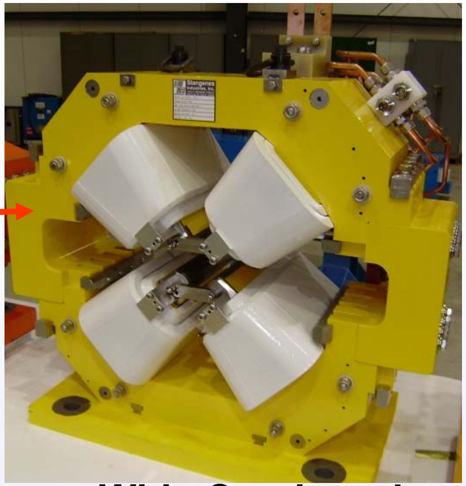
See Paper MO3PBI02, S. Krinsky, “Accelerator Physics Challenges for the NSLS-II Project”

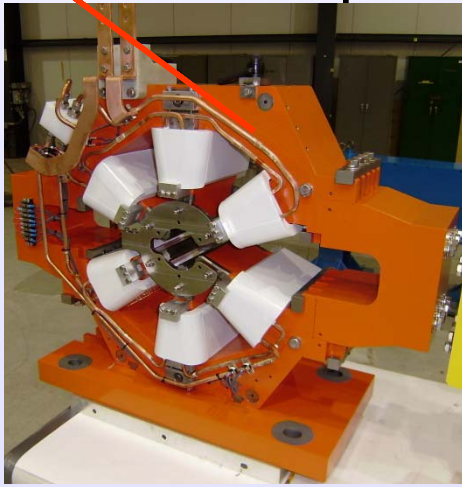
Main NSLS-II Storage Ring Magnets (over 1000 in total)


Correctors (slow & fast)

A typical cell of NSLS-II




Wide Quadrupoles & Sextupoles




Regular Sextupoles & Quadrupoles


Dipoles (35mm & 90 mm)

See Paper MO6PFP008, J. Skaritka, et al., "Design and Construction of NSLS-II Magnets"

Prototype Magnet Production and Testing Completed

- Storage ring magnet prototype production contracts were placed in the spring of '08 with *vendors around the world*
  - Vendor A — One 90mm Quad, One 76mm Sextupole
  - Vendor B — One 35mm Dipole, 90mm Quad, 76mm Sextupole, 66mm Quad
  - Vendor C — One 90mm Dipole, two 66mm Quadrupoles, one 68mm Sextupole
- Manufacturing began in late summer '08
  - All construction and specified testing on site was completed in a short period
    Four to six month from the time given "OK to Proceed"
  - All prototype magnets were delivered to BNL by March '09
- Measurements have now been performed on all prototype magnets at BNL

Courtesy: John Skarita

See Paper MO6PFP008, J. Skaritka, et al., "Design and Construction of NSLS-II Magnets"

A Word from Our Sponsor

“Requests for Proposals” for NSLS-II Magnets is now being advertised on the FedBizOpps.Gov Web site

Potential vendors are encouraged to submit proposals for competitively bidding

Progress in

Low Field Dipole Design

Development in Iron Dominated Dipole Designs

Magnet in the existing NSLS complex (a typical design for iron dominated magnets)

- **Mechanical length** of a magnet is usually determined by the coil length
- **Magnetic length** of an iron dominated magnet is determined by the yoke length
- The physical space consumed by the ends of the coil is a significant waste.

Next slide: How this waste can be avoided in low field magnets

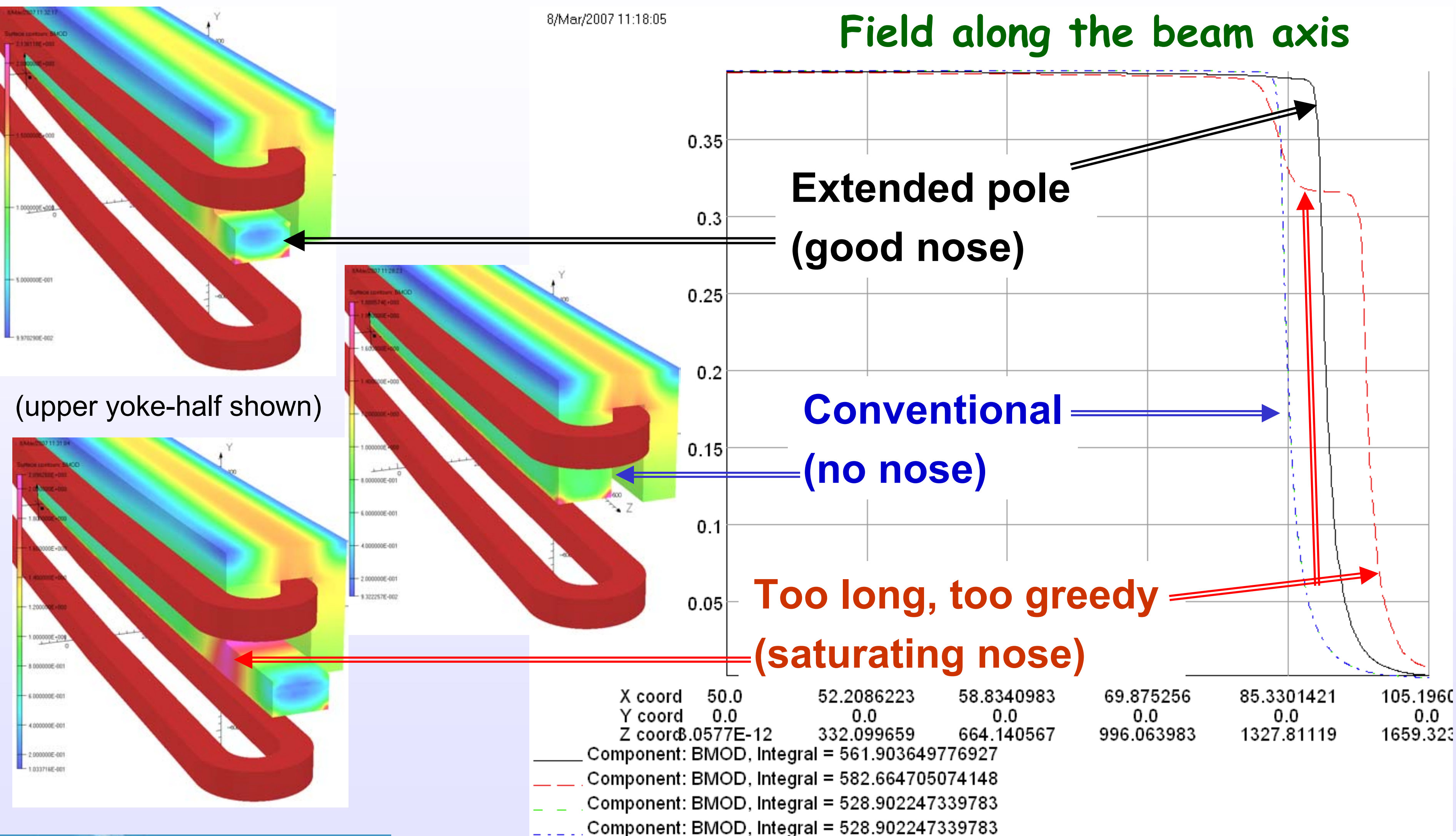
(0.4 T in NSLS-II)

Unique Feature in NSLS-II Storage Ring Dipole
Extended Pole or Nose

- *"Extended Pole"* or *"Nose"* essentially eliminates the waste of space by the coil ends.
- Coils are moved vertically up and down.
- Poles are extended to the length of the coil
  - Nose sticks out.
- This increases the magnetic length.
- The magnetic length of the dipole ~(pole + one aperture) could now be longer than the mechanical length (as long as the nose iron is not saturated).
- In NSLS-II, it saved (freed-up) ~10 meter (~1.5%) space, which is significant.
- This feature could be useful in future projects involving low field magnets.

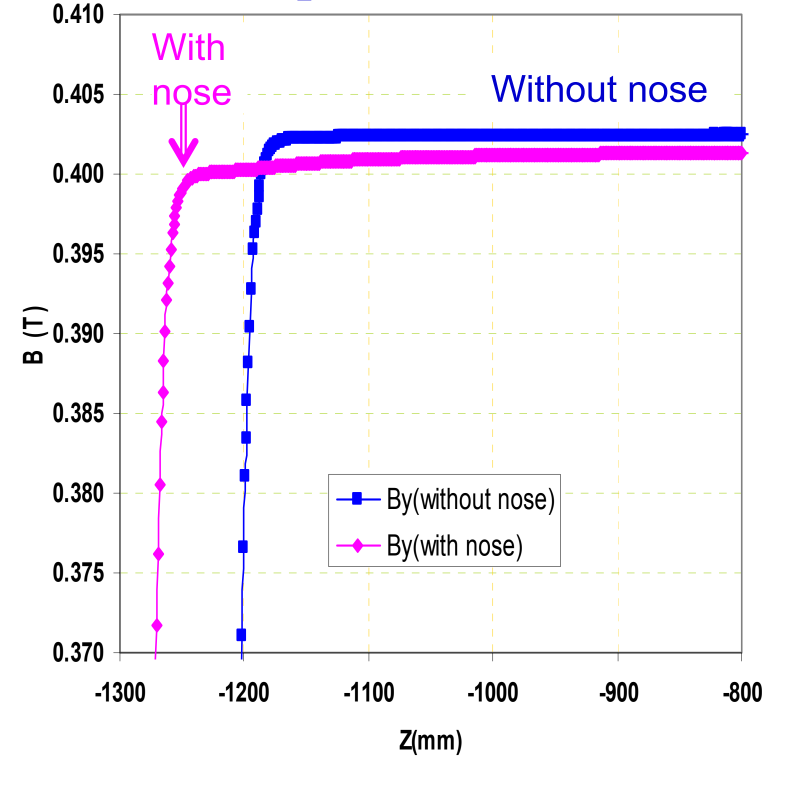
Magnet in the existing NSLS complex

Magnetic Design of the Nose Piece



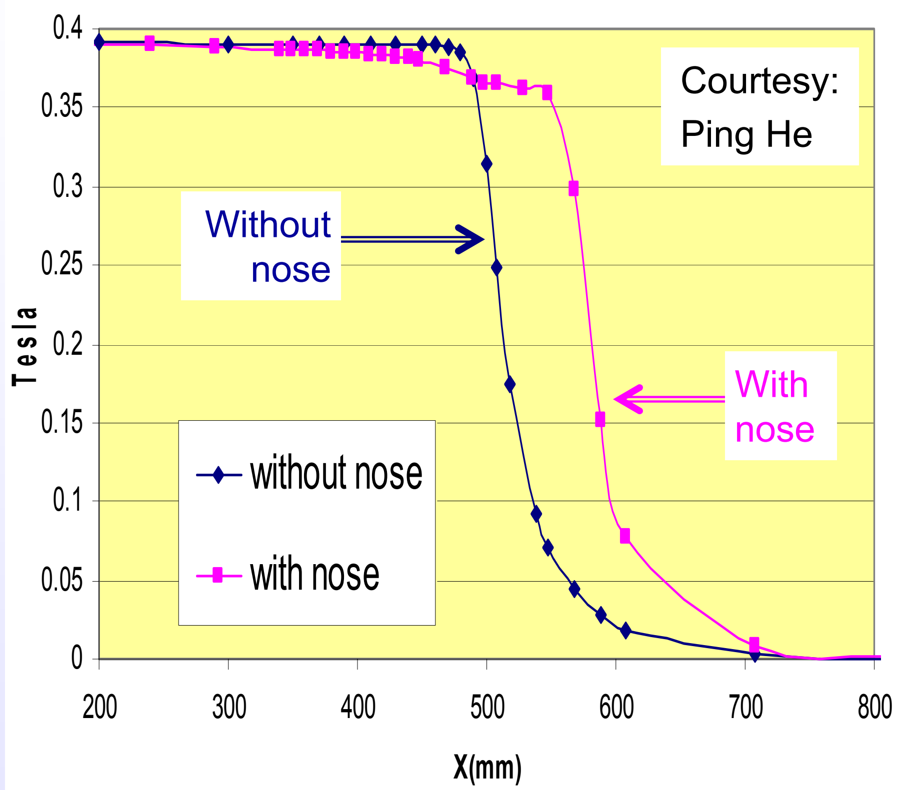
Calculations and Measurements of Field Extension by Nose

Computer model



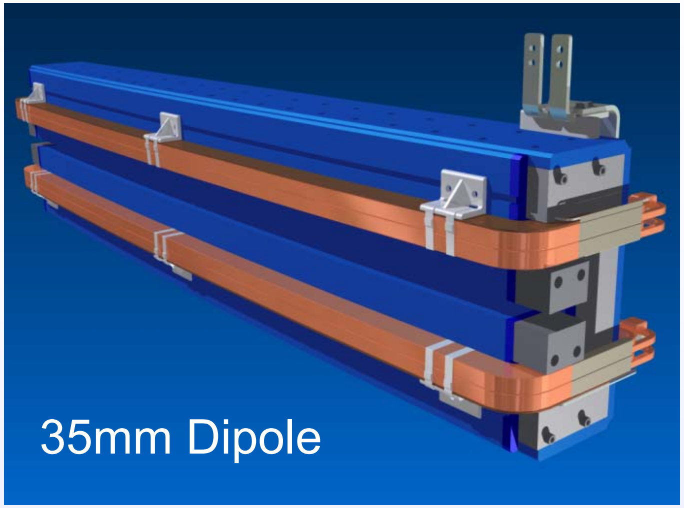
Note different scales for calculations and measurements

Measurements

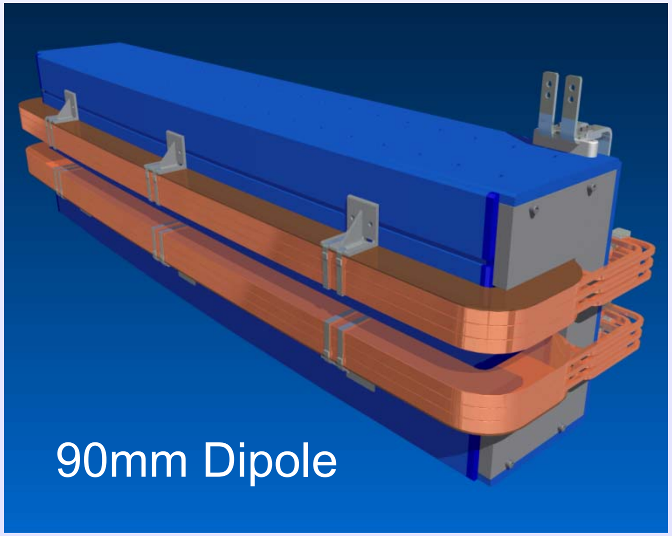


- A gradual decrease in field along the axis in both calc. & meas. (small, see scale).
- A larger local drop of field in nose region (see measurements) is caused by a saturating nose likely due to a poor choice of material by vendor in this particular R&D magnet.

Other benefits of the Nose Piece



- In typical magnets, the ends of the yoke are parallel for the ease of construction. However, this causes the beam to enter at an angle.
- Nose piece offers a convenient way to convert it to a "*sector magnet*" with minor adjustment in the shape of the nose pieces.



- NSLS-II uses fifty-four 35mm aperture dipoles and six 90mm aperture dipoles.
- There is a desire to match the field fall-off (focusing) in the ends in addition to harmonics.
- Nose design in 35mm causes slower fall-off (better match with 90mm) and further shaping of it allows more fine tuning.

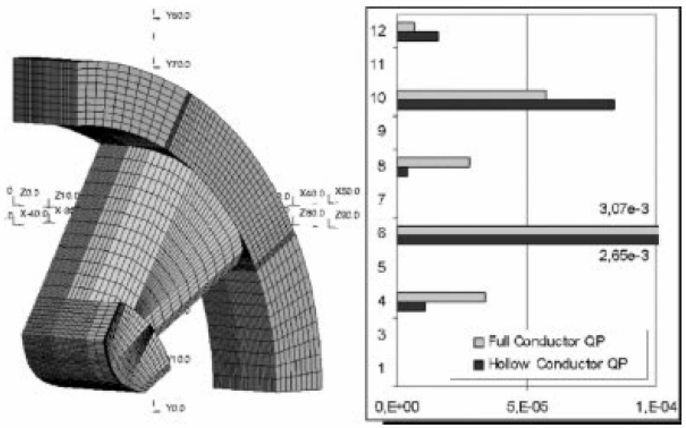


Fig. 3. Left: 3-D view of the basic QP magnet design. Right: 3-D harmonics (integrated gradient) of both QP magnet designs. Values are normalized to the fundamental ($n = 2$) harmonic.

All the DTL magnets will be the same size to allow standardization and to reduce the size of the DT. This design improves the shunt impedance, thus minimizing power losses in the machine walls. The DT assemblies built for the prototype have the same external dimensions, as indicated in Table I.

III. MAGNETIC SIMULATIONS

The QP magnet poles have been designed using Vector Fields Opera3D electromagnetic code. The main goal was to minimize saturation in both poles and yokes while maintaining small dimensions, the required gradient, and as low a current density as possible. High-order harmonics considerations were of secondary importance.

A 2-D cross section has been designed to satisfy these requirements. The conical pole shape has been optimized to minimize saturation effects and allows to have enough space to insert the conductors. Several magnetic materials have been used for the computations, mainly standard iron and iron cobalt "Permendur" alloy. The 3-D computations led to a "mushroom-shaped pole": the longitudinal extensions allow to decrease the pole tip saturation and to enlarge the magnetic length of the magnet (see Fig. 3).

From this common standard design two separate designs have been derived, to be fitted in two different drift tube assemblies.

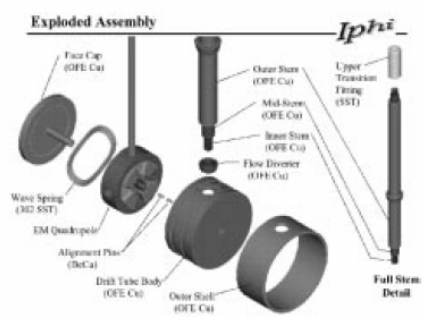


Fig. 4. Exploded view of the conventional drift tube.

IV. CONVENTIONAL DRIFT TUBE MAGNET ASSEMBLY

The manufacturing process is the same for both models of DT assemblies. After pre-machining of the DT elements and the assembly of the magnets, both DT types are electron beam welded. Vacuum integrity is then verified and final machining of the DT completed.

The first DT assembly has been designed by AES [3]; its

A review of literature revealed that a somewhat similar concept has been used by Bernaudin, et al., in quadrupoles for a Proton Drift Tube Linac at SACLAY.

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 12, NO. 1, MARCH 2002 43

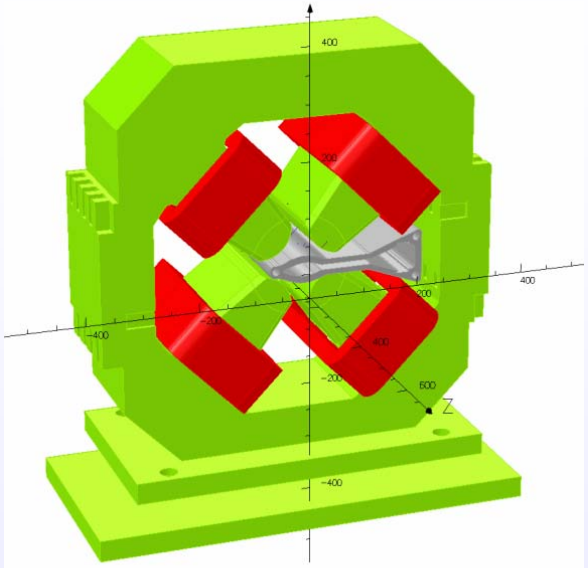
Technical Innovations for a High-Gradient Quadrupole Electromagnet Intended for High Power Proton Drift Tube Linacs

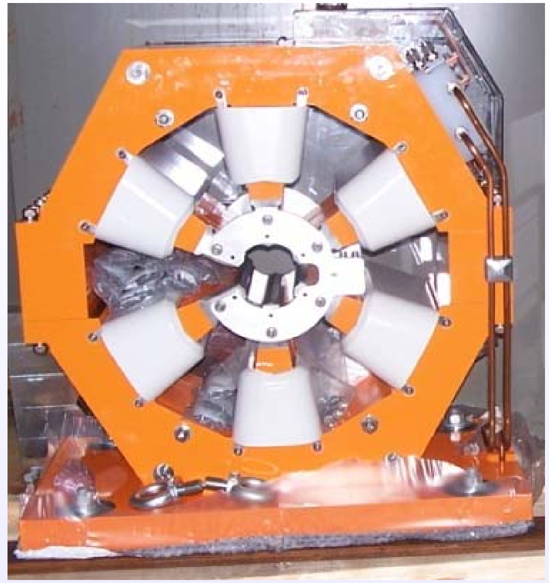
P.-E. Bernaudin, O. Delferrière, M. Painchault, and C. E. A. Saclay

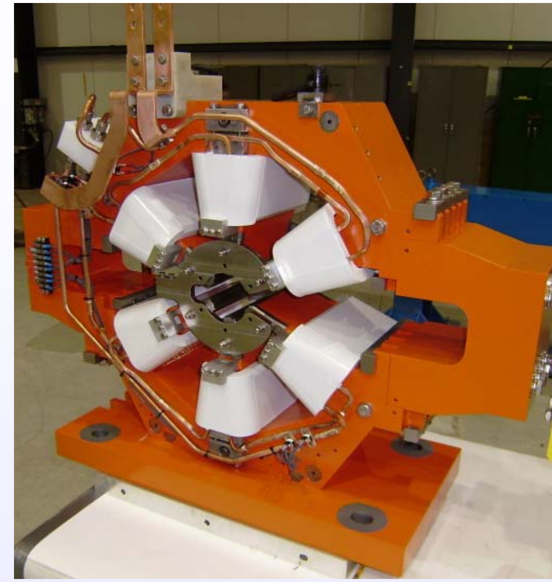
Progress in

Quadrupole and Sextupole Design

Magnetic Design of NSLS-II Quadrupoles and Sextupoles







• Even if field quality is perfect in 2-d, ***end chamfers*** must be used later to obtain good integral field quality.

• Using end chamfers as an integral part of the overall design optimization from the beginning makes sense in short magnets.

• Basic magnet symmetry is broken in wide sextupoles.

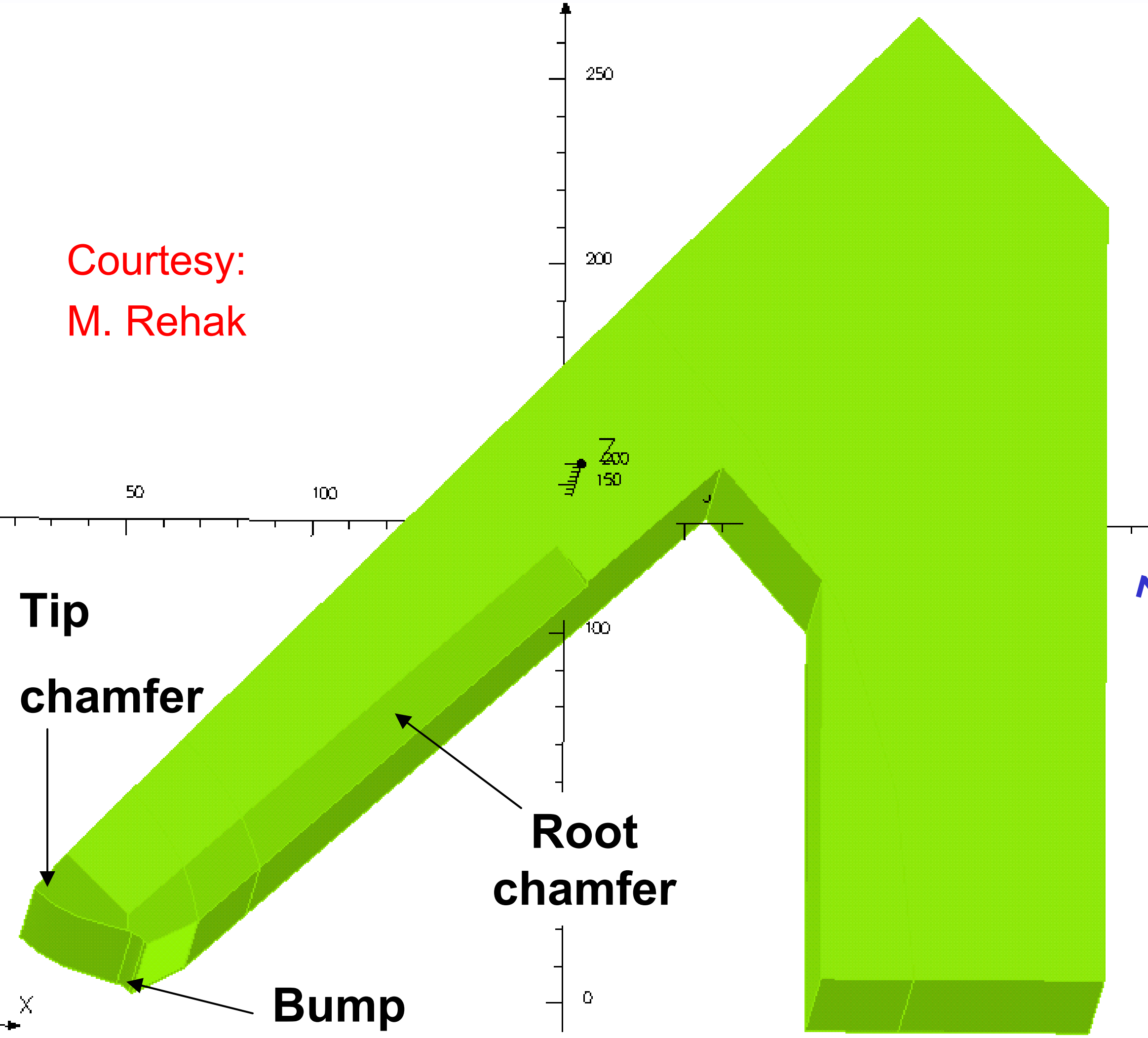
See Papers:

MO6PFP007, **M. Rehak, et al.,** "Design and Measurement of the NSLS-II Quadrupoles"

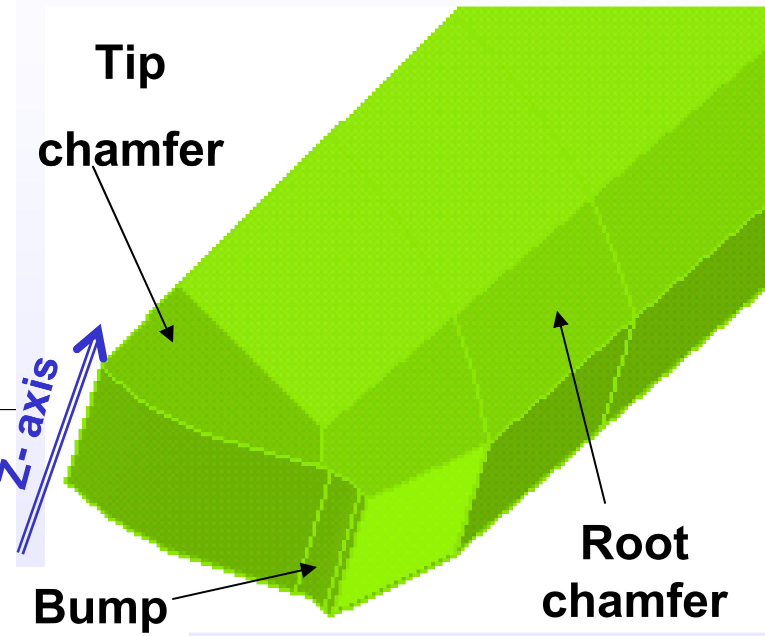
MO6PFP010, **C. Spataro, et al.,** "Design and Measurement of the NSLS-II Sextupoles"

Techniques Used in Field Quality Optimization of NSLS-II Quadrupoles and Sextupoles

Courtesy:
M. Rehak



3 controls for first 3 allowed harmonics for multipoles



See Paper:

MO6PFP007, **M. Rehak, et al.,** "Design and Measurement of the NSLS-II Quadrupoles"

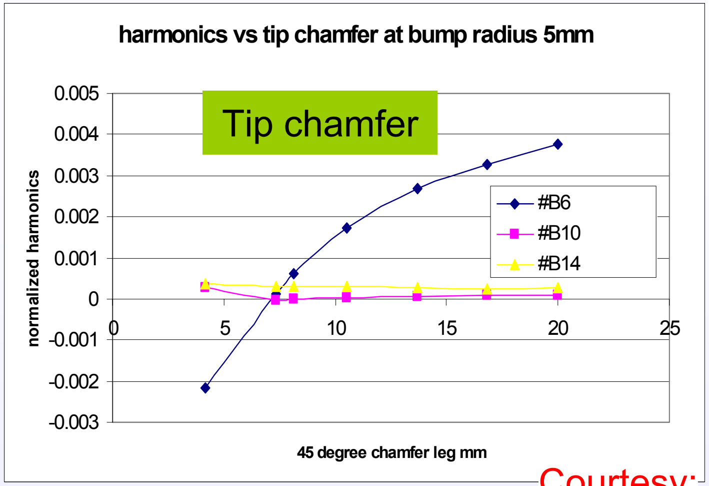
Techniques Used in Field Quality Optimization of NSLS-II Quadrupoles and Sextupoles

- Any perturbation in pole (chamfer or bump) changes the harmonics.
- The change depends on the location and size of the perturbation

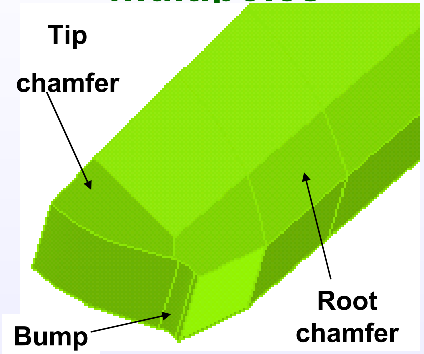
$$\delta b_n \propto B_r(r,\theta) \quad \sin(n\,\theta)$$

where B_r is the radial component of the field at (r,θ) and n is the harmonic number.

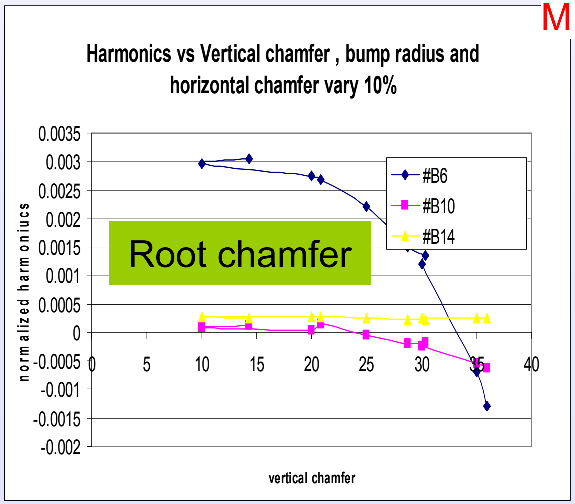
- Perturbations consistent with magnet symmetry will change only the allowed harmonics.
- For example, a narrow tip chamfer at pole will generate allowed harmonics with alternating changing sign
- Root chamfers are introduced to save coils space & reduce saturation. In quad it makes negative changes in b_6 & b_{10} which is used in optimization.

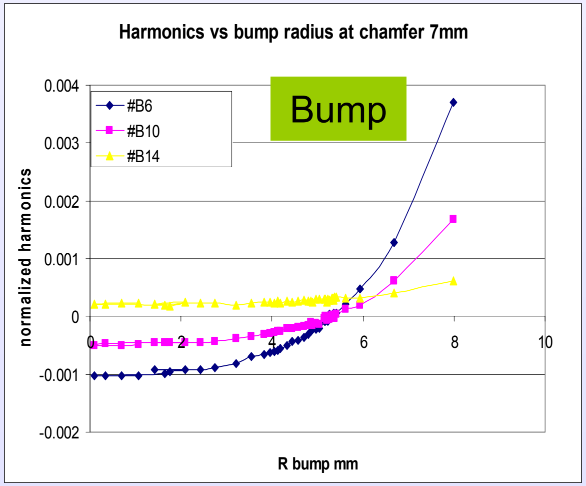


3 controls for first three allowed harmonics for multipoles



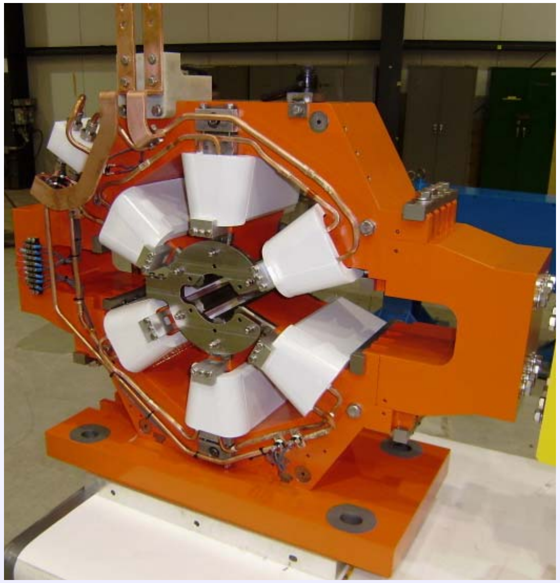
Courtesy: M. Rehak



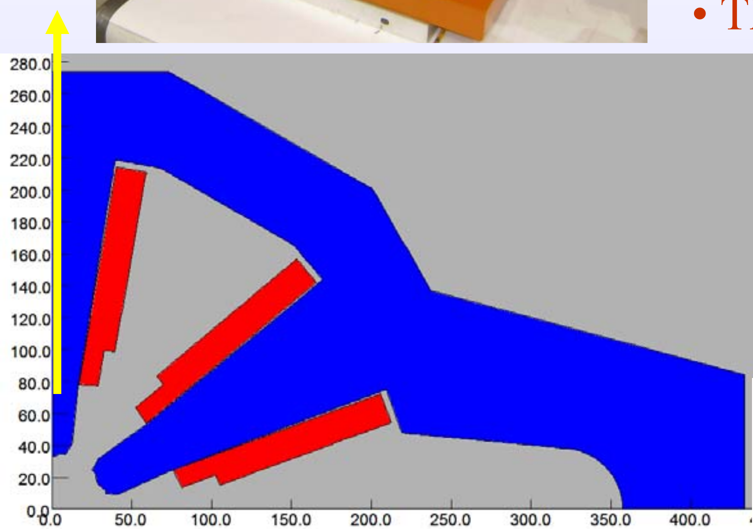


MO6PFP007, **M. Rehak, et al.,**
"Design and Measurement of the NSLS-II Quadrupoles"

A Technique for Minimizing Semi-allowed Harmonics



- Wide sextupole design accommodates X-ray transport.
- However, it breaks the ideal six fold symmetry and creates "non-allowed" or "semi-allowed" harmonics (b_1, b_5, b_7, etc.).
- A technique has been developed to minimize these harmonics, which could be used in future machines as well.
- Compensate this asymmetry by another deliberate asymmetry by moving the poles in vertical plane away from the center (adjustment required : only ~70 μm).
- This is natural for floating pole design used in NSLS-II.



n	bn(corrected)	bn(original)
1	-8.1	-37.6
5	0.0	-4.5
7	-0.25	-0.36

Please Visit: http://www.bnl.gov/magnets/staff/gupta/Talks/NSLS2-internal/

Ramesh Gupta, "*Magnetic Design Studies of the Sextupole*,"

Prototype Lattice Magnet Design Review, January 28, 2008.

Overall Experience with Prototype Magnet Program

• A purpose of the prototype magnet program was to establish what industry could produce given the stringent technical, cost and schedule constraints.

• The program was a success with most of the prototype magnets meeting expectations (one magnet was returned due to a flaw in manufacturing).

• While evaluating magnet performance, it was concluded that all design and manufacturing issues are resolvable, thus reducing the programmatic risk.

Courtesy: John Skarita

Progress in Magnet Alignment

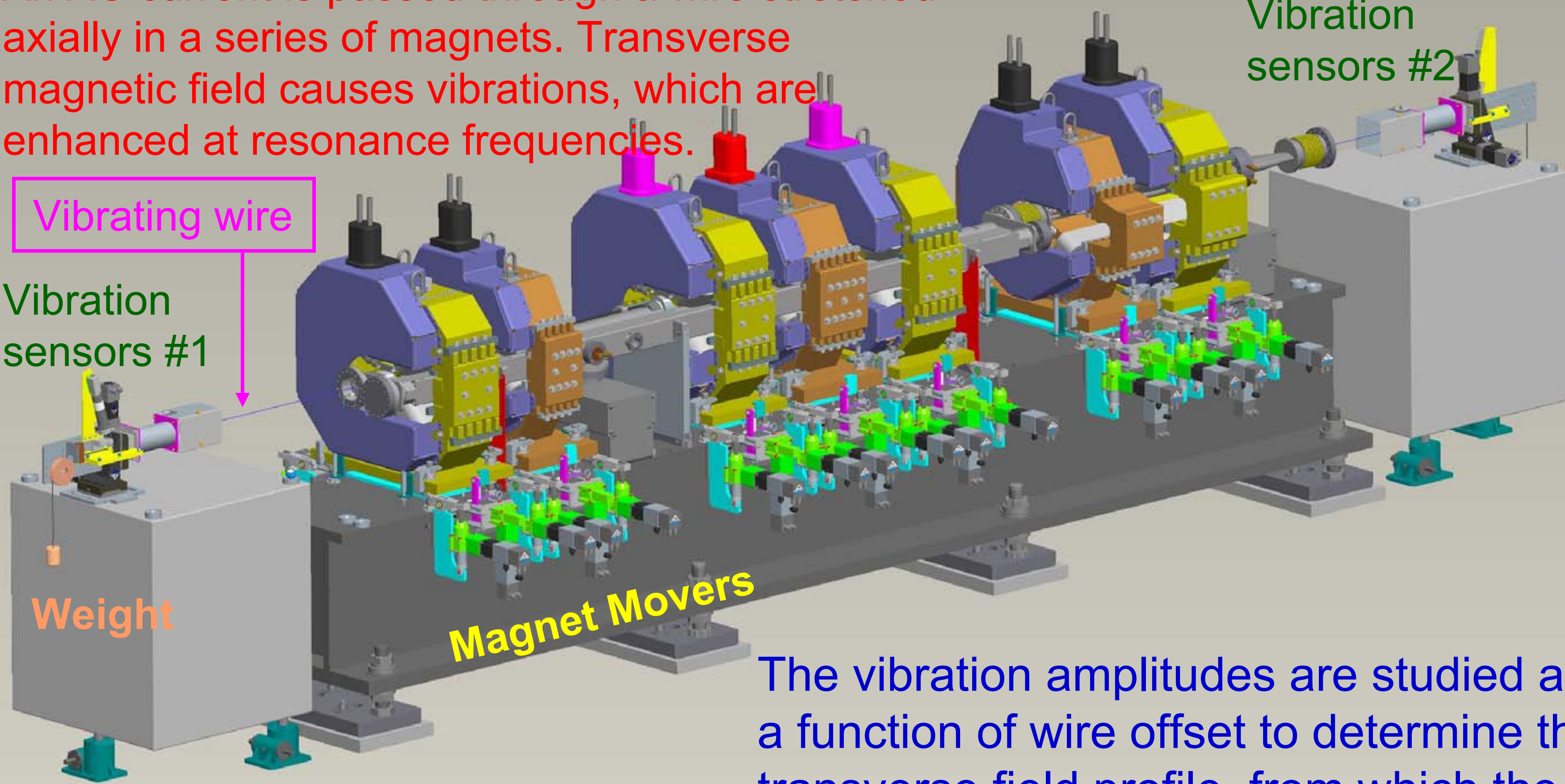
Precision Alignment of Multipoles in NSLS-II

- For optimum performance, the magnetic axes of quadrupoles and sextupoles in NSLS-II should be aligned to better than ±30 microns.
- Optical survey accuracy (50-100 micron) is inadequate to achieve the required tolerance.
- It is difficult, and expensive, to maintain the required machining and assembly tolerances in a long support structure (~5 m long girder) holding several magnets.
- An advanced system based on vibrating wire technique (originally developed at Cornell) has been built to achieve the required alignment using direct magnetic measurements in a string of magnets.

Courtesy: Animesh Jain

Vibrating Wire Setup With a Production Girder

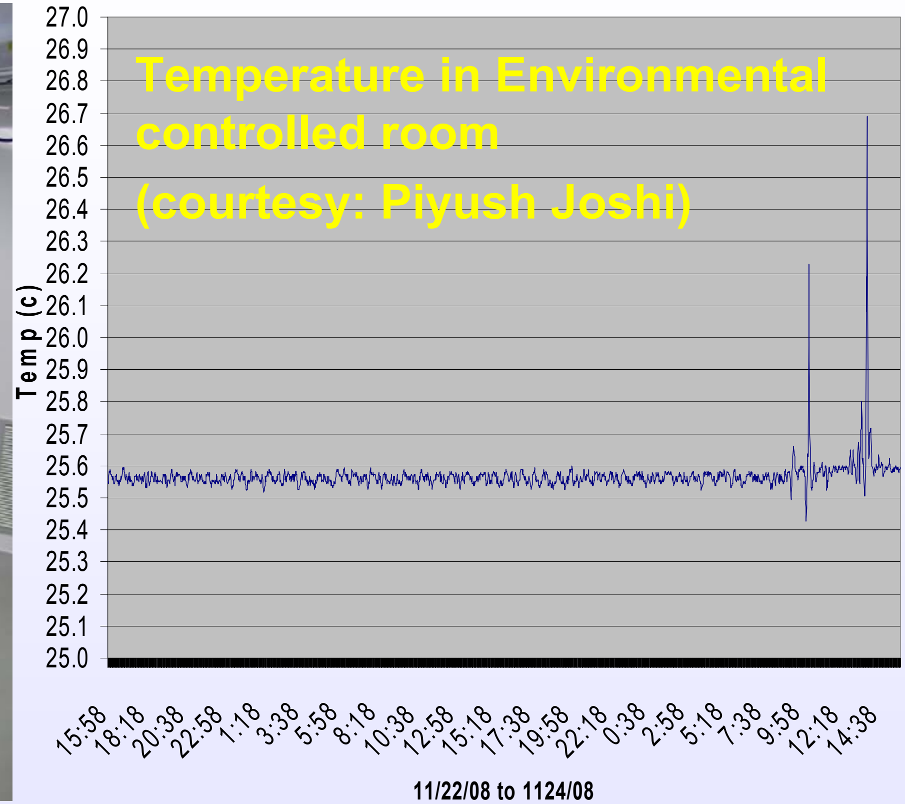
An AC current is passed through a wire stretched axially in a series of magnets. Transverse magnetic field causes vibrations, which are enhanced at resonance frequencies.



The vibration amplitudes are studied as a function of wire offset to determine the transverse field profile, from which the magnetic axis can be derived.

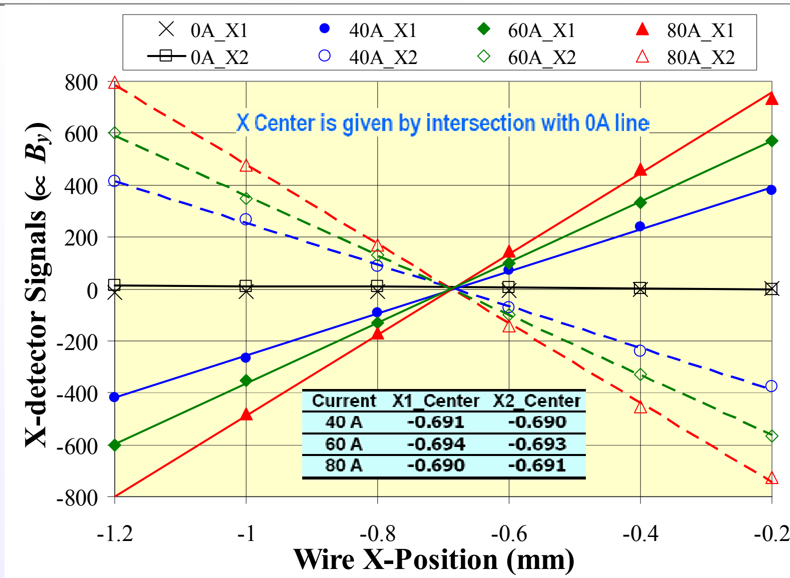
Courtesy: Animesh Jain (to be published)

Alignment Measurements in Environment Controlled Room

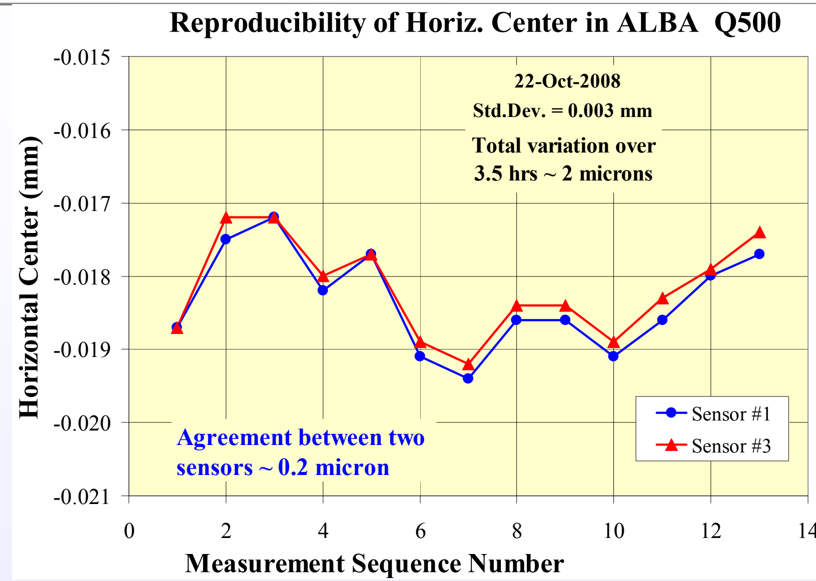


- The Precision Alignment Environmental Room has been completed.
- Temperature control of +/- 0.02C has been demonstrated (spec was only +/- 0.2 C).
- Survey and Installation studies to simulate the tunnel environment are underway.
- Measurements performed so far were ***not*** made in this temperature controlled room.

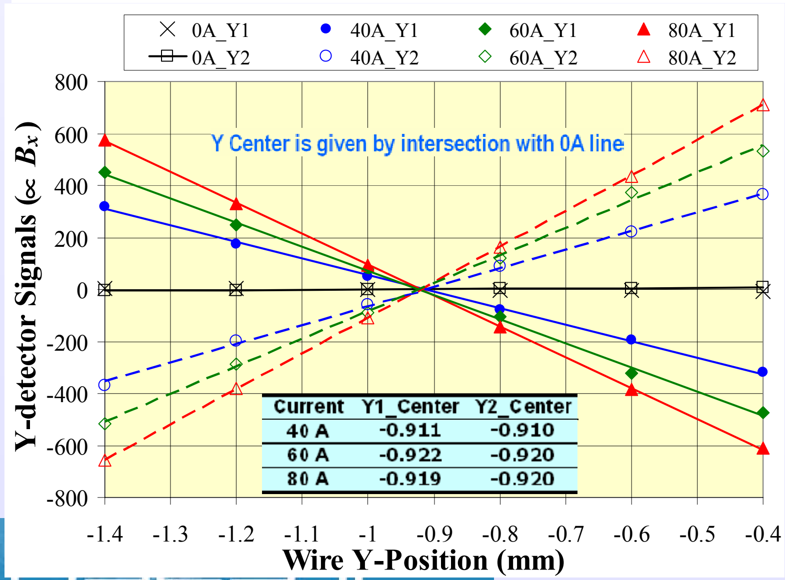
Determination of Quadrupole Center



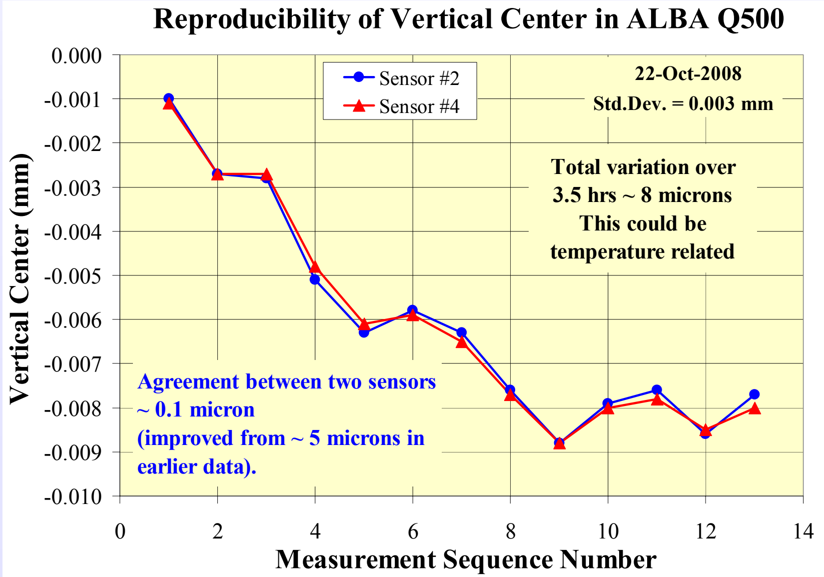
Current	X1_Center	X2_Center
40 A	-0.691	-0.690
60 A	-0.694	-0.693
80 A	-0.690	-0.691



Results of significant develop-ment and analysis

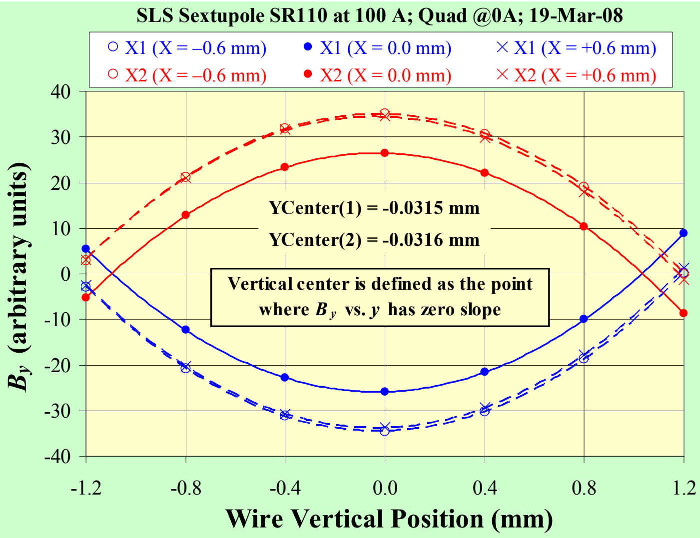


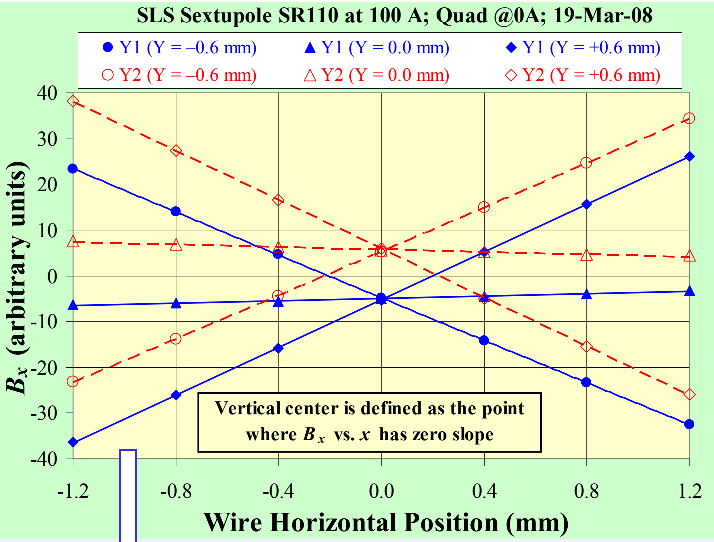
Current	Y1_Center	Y2_Center
40 A	-0.911	-0.910
60 A	-0.922	-0.920
80 A	-0.919	-0.920



Courtesy: Animesh Jain (to be published)

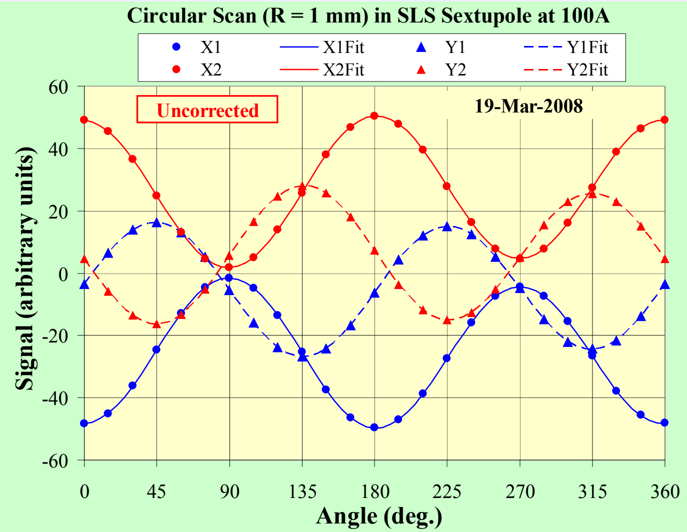
Determination of Sextupole Center

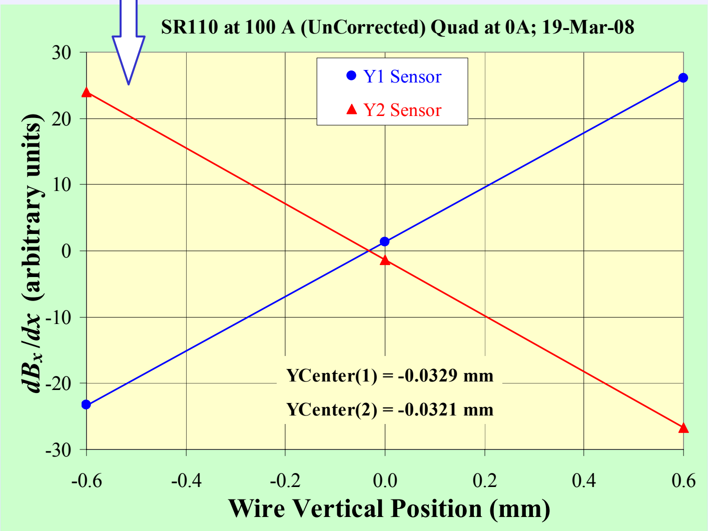




Sextupole center can be determined using four methods (a good way to check internal consistency).

Different methods show a standard deviation of only a few microns.





A state-of-the-art vibrating wire system provides an absolute accuracy < 5 μm, sufficient to meet NSLS-II spec.

Courtesy: Animesh Jain (to be published)

Similar plots for horizontal

Building and Commissioning Machines

With a Tightly Packed Lattice

Advance Knowledge of the Challenges

Makes Us Better Prepared

Field Quality Distortions in a Tightly Packed Machine

- NSLS-II storage ring is a tightly packed machine with very small gaps (~150 mm) between adjacent magnets and other hardware (such as vacuum chamber supports and ion pumps, etc.).
- This may generate significant field distortions (or interaction harmonics) that could have a significant impact on the performance of machine.
- A program to measure these interference effects has been carried out using the magnets received on loan from other synchrotron radiation sources and also some prototype magnets for NSLS-II.
- Results from these measurements are summarized along with the comparison with calculations in a few cases.

Influence of Nearby Magnets on Field Quality

Configurations for Interaction Studies (between two or more magnets)

Field measurements to study interaction between two adjacent magnets:

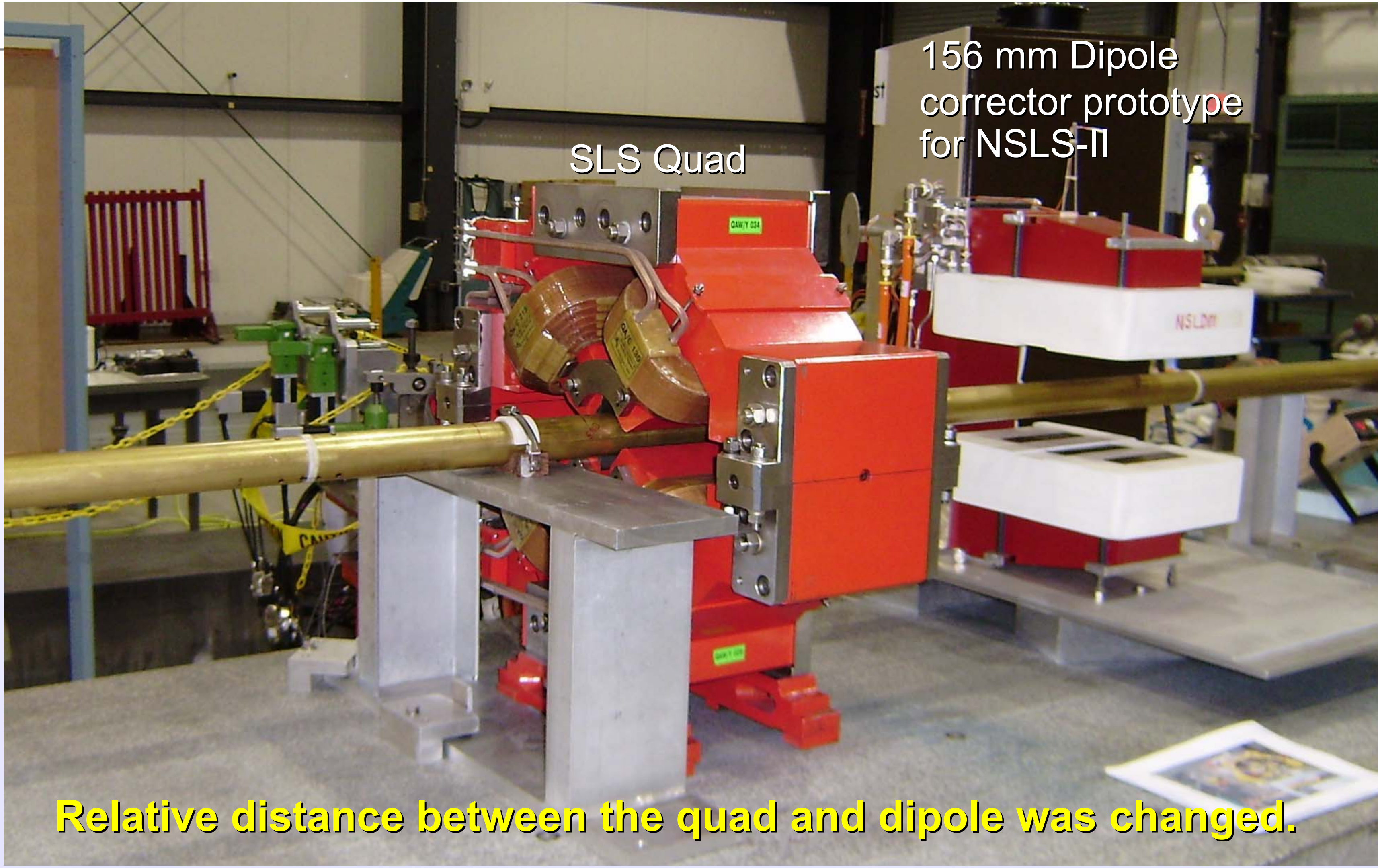
- SLS Sextupole – **SLS Quad** – SLS Sextupole ⟸
- SLS Quad – **SLS Sextupole** – SLS Quad
- **SLS Quad** – NSLS-II 156 mm Dipole Corrector ⟸
- **SLS Quad** – 156 mm Dipole (Normal+Skew; 10A fixed)
- SLS Quad – **156 mm Dipole (Normal+Skew)**
- **SLS Quad** – NSLS-II 100 mm Dipole Corrector
- **SLS Quad** – 100 mm Dipole (Normal+Skew; 10A fixed)
- ALBA Sextupole – **ALBA Quad** – ALBA Sextupole
- ALBA Quad – **ALBA Sextupole** – ALBA Quad

[Blue = Powered at fixed current; **Bold** = full excitation curve

A large number of studies performed
Only select two will be presented

Courtesy: Animesh Jain

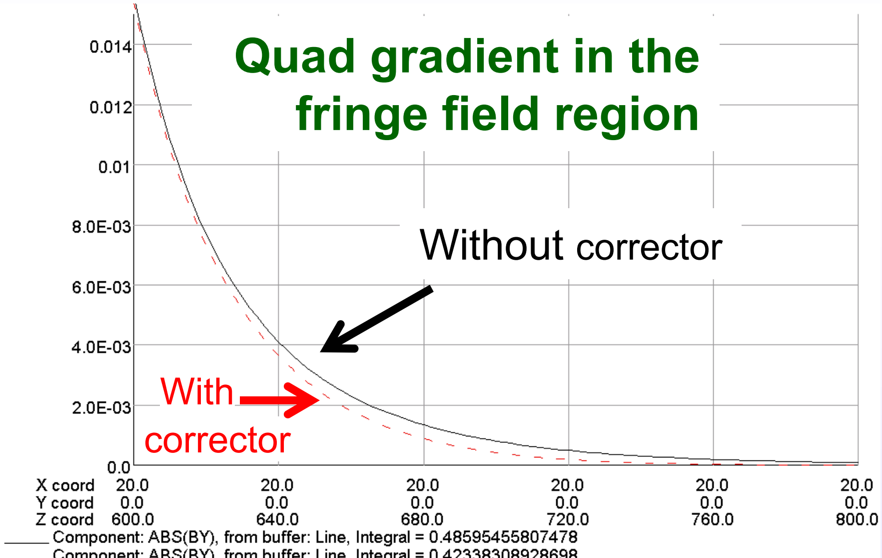
SLS Quad near 156 mm Dipole Corrector



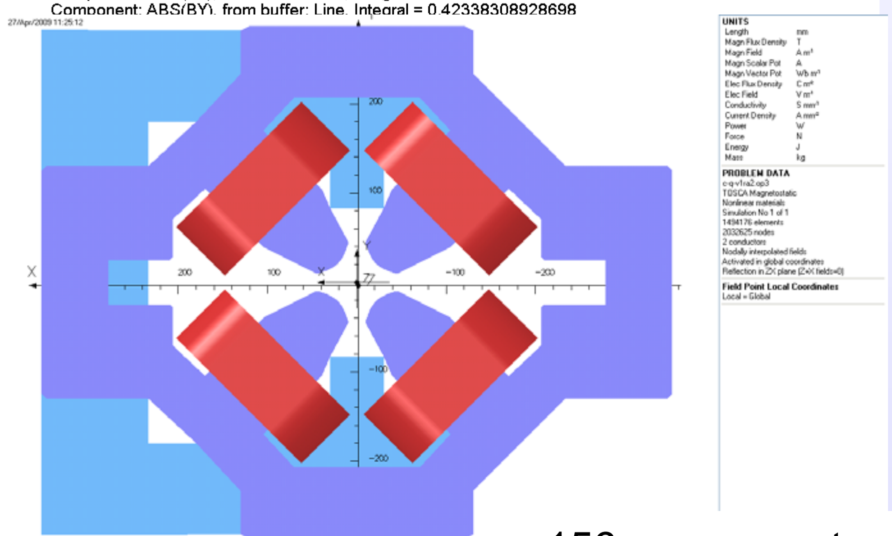
Minimum Yoke-to-Yoke gap = 130 mm

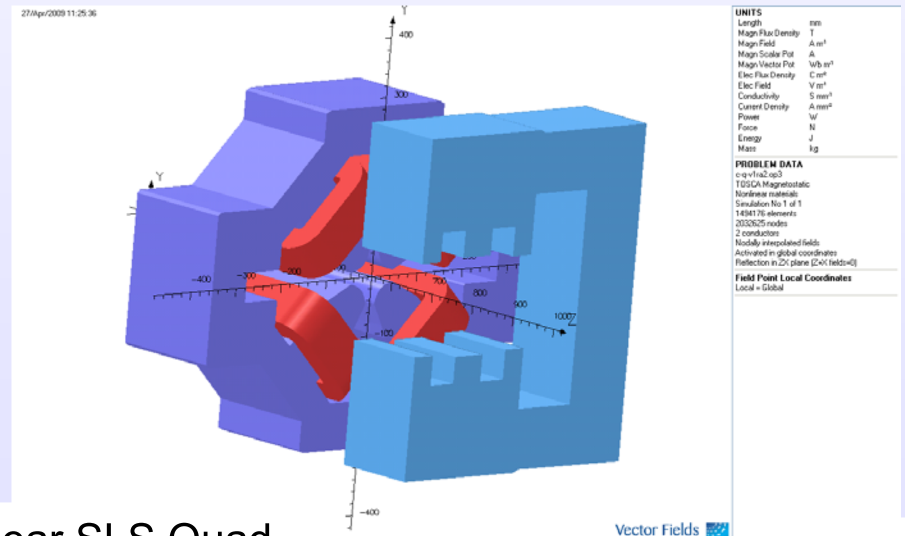
Courtesy: Animesh Jain (to be published)

Model Calculations for Interaction between Quadrupole and Dipole Corrector



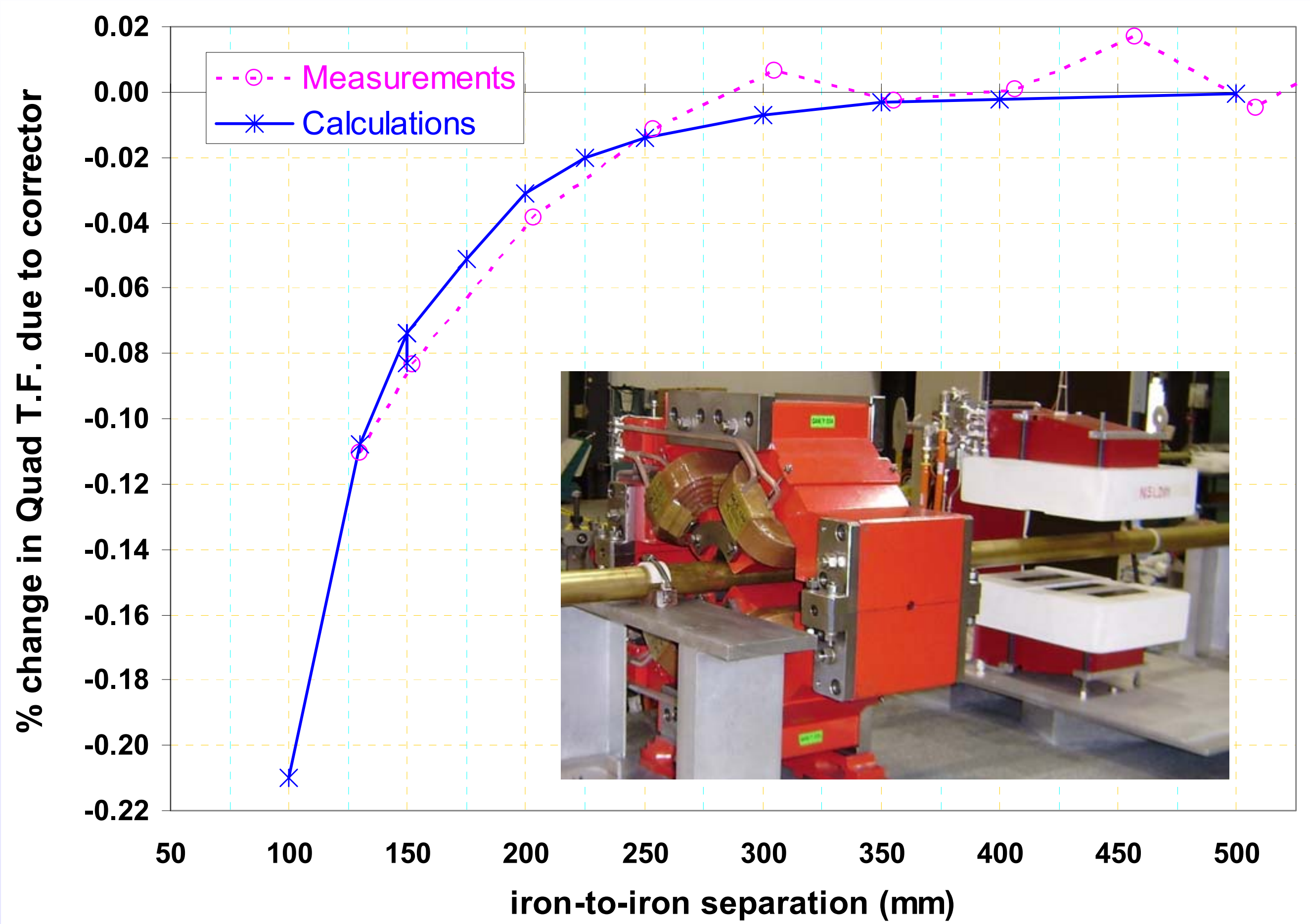
- **Maximum influence in quadrupole field was seen when the dipole corrector was not powered.**
- **Iron of the dipole provides a shunt path to the fringe field of the quadrupole, reducing its integrated field strength.**
- **No serious influence on field harmonics was seen in this case.**





156 mm corrector near SLS Quad

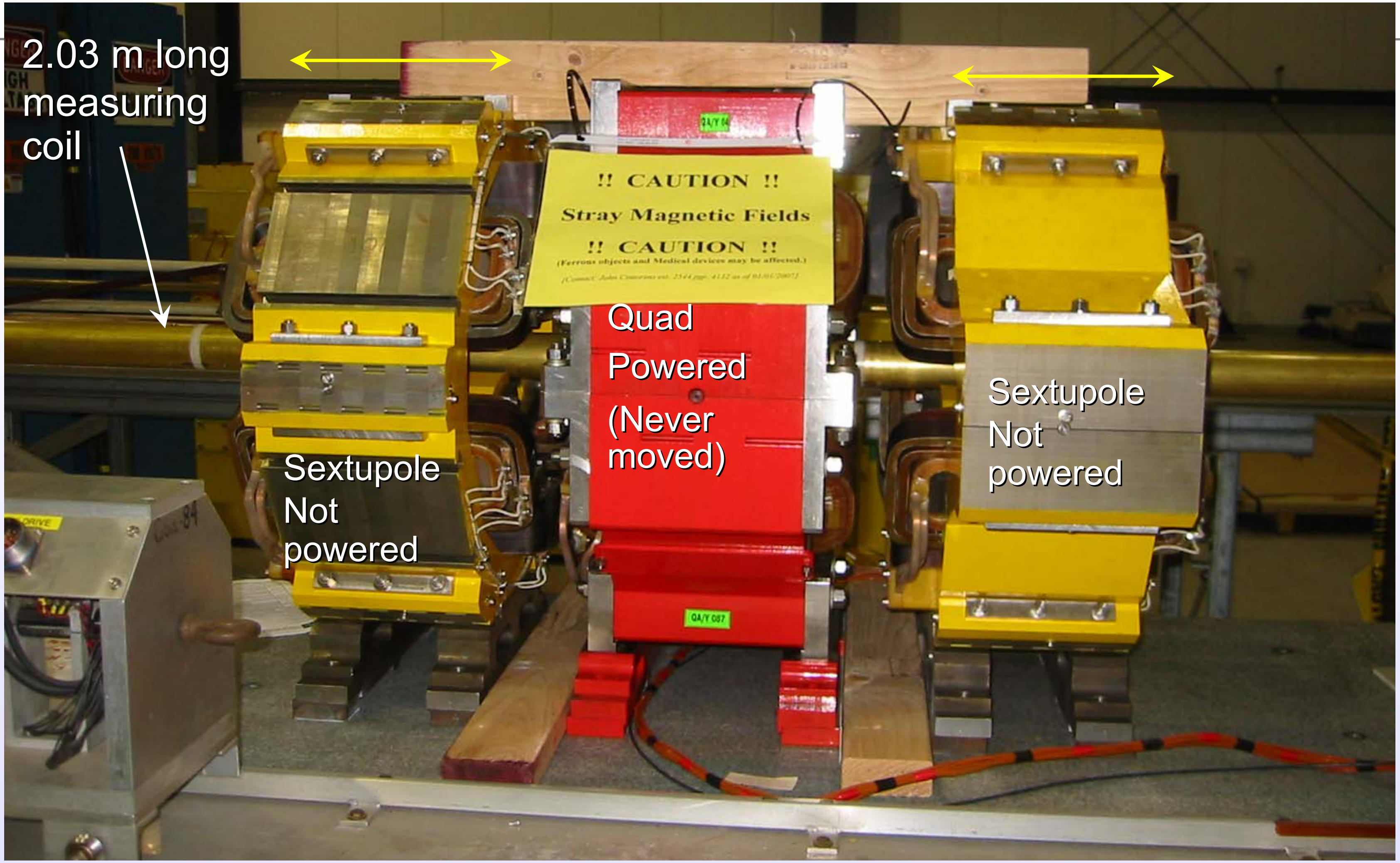
Comparison between Calculations and Measurements



- Quadrupole transfer function decreases by ~1 part in 1,000 when the iron to iron separation is ~130 mm.
- Good agreement between calculations and measurements (a few part in 10,000), limit of accuracy of both measurements and calculations.

156 mm corrector near SLS Quad

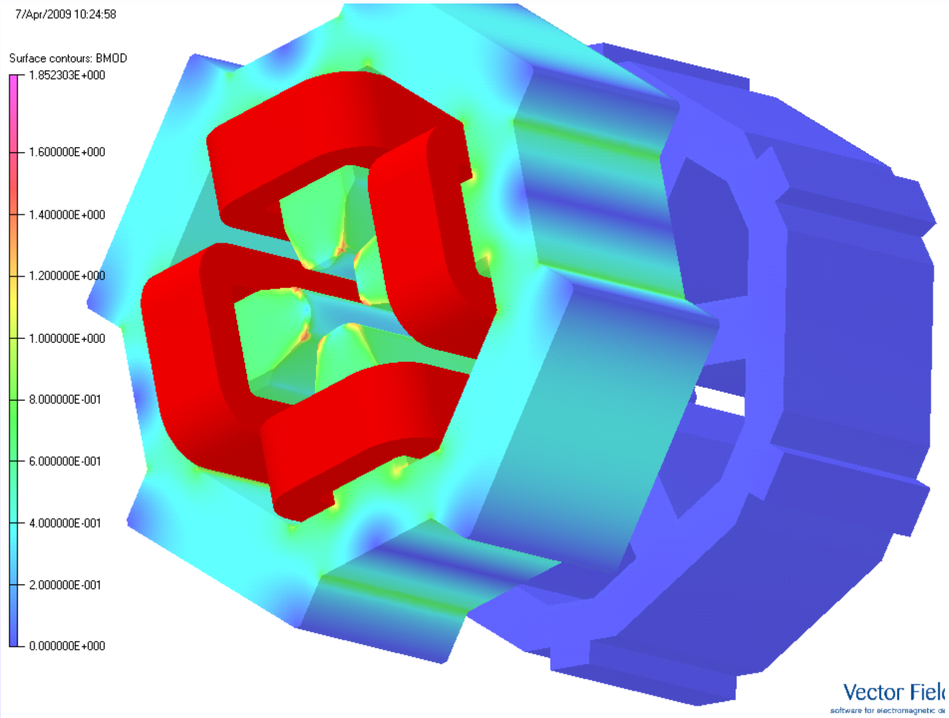
SLS Quadrupole between Sextupoles



Minimum Yoke-to-Yoke gap = 136 mm

Courtesy: Animesh Jain (to be published)

Computer Modeling of Quad-Sextupole Field Interaction Studies



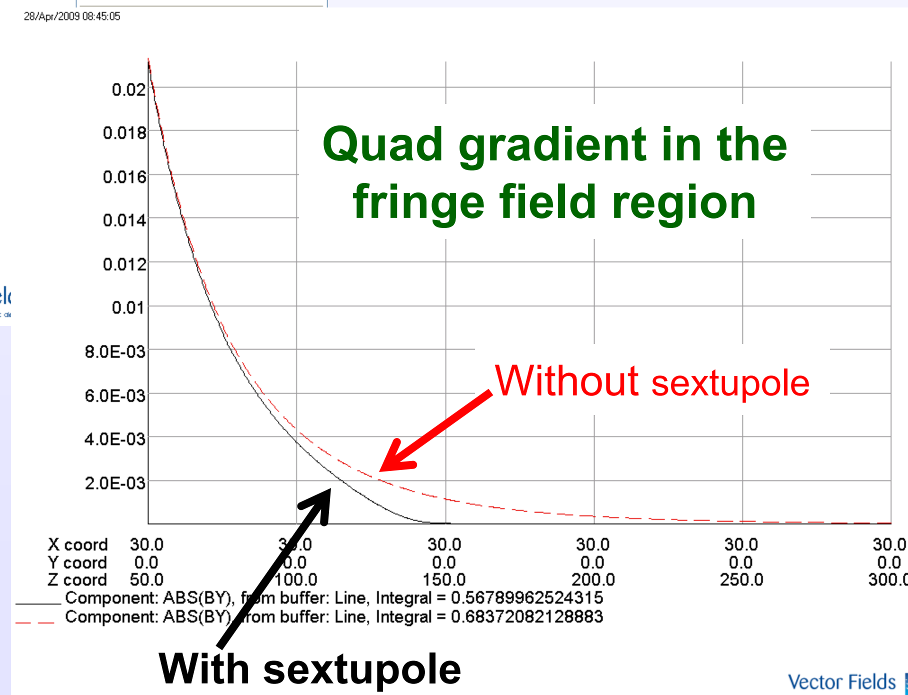
UNITS

Length	mm
Magn Flux Density	T
Magn Field	$A\,m^{-1}$
Magn Scalar Pot	A
Magn Vector Pot	$Wb\,m^{-1}$
Elec Flux Density	$C\,m^{-2}$
Elec Field	$V\,m^{-1}$
Conductivity	$S\,m^{-1}$
Current Density	$A\,m^{-2}$
Power	W
Force	N
Energy	J
Mass	kg

PROBLEM DATA
quad-sext-136-s3-uadratic.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
10301463 elements
13801417 nodes
2 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates
Local = Global

- **Sextupole is not powered.**
- **The influence of the sextupole iron on the quadrupole is observed.**

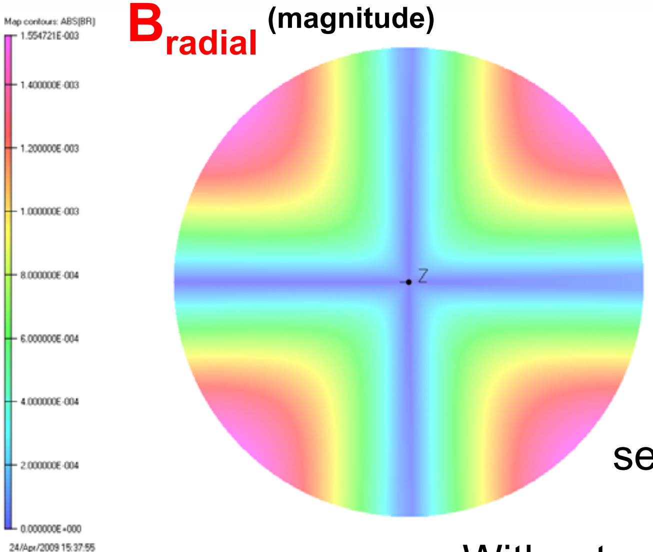


Iron of the sextupole provides a shunt path to the fringe field of the quadrupole, reducing its integrated field strength (field gradient)

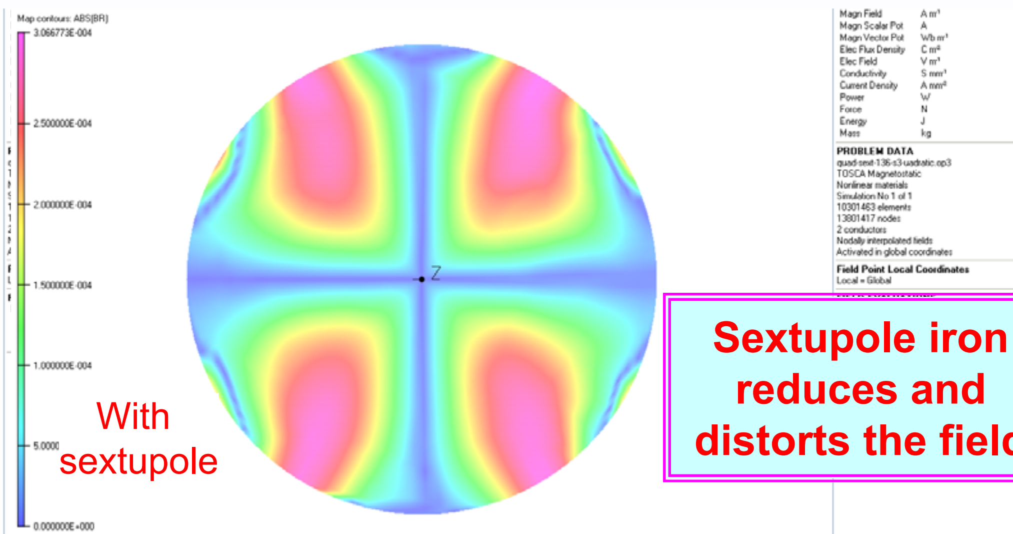
Change in Quad fringe Field due to Sextupole

(change in radial component at sextupole due to sextupole iron)

B_{radial} (magnitude)



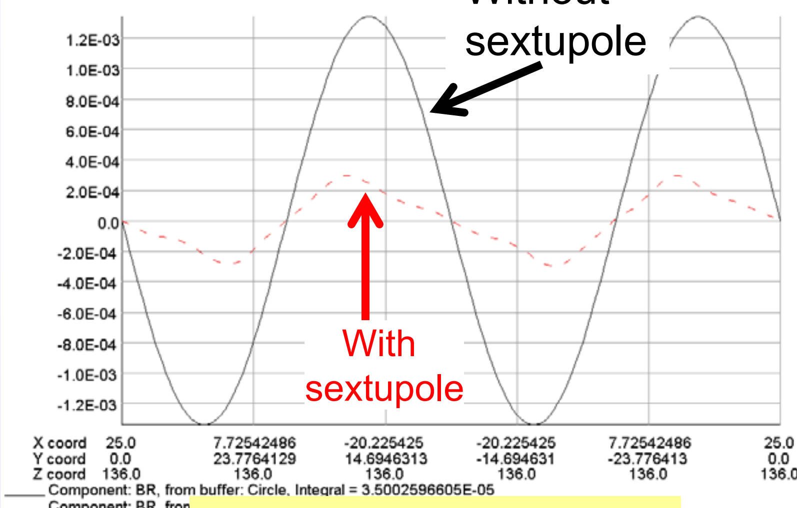
Without sextupole



With sextupole

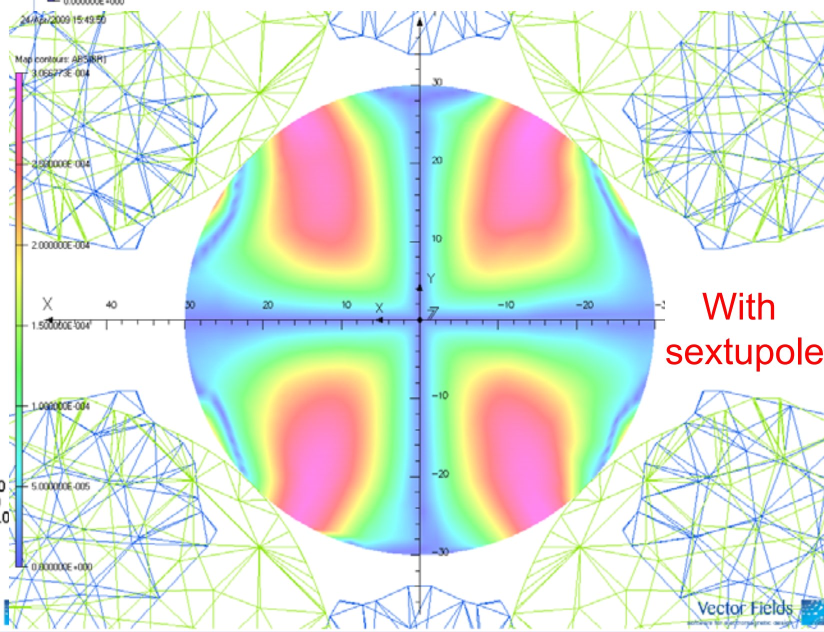
Sextupole iron reduces and distorts the field

Without sextupole



With sextupole

Angular variation of B_{radial}

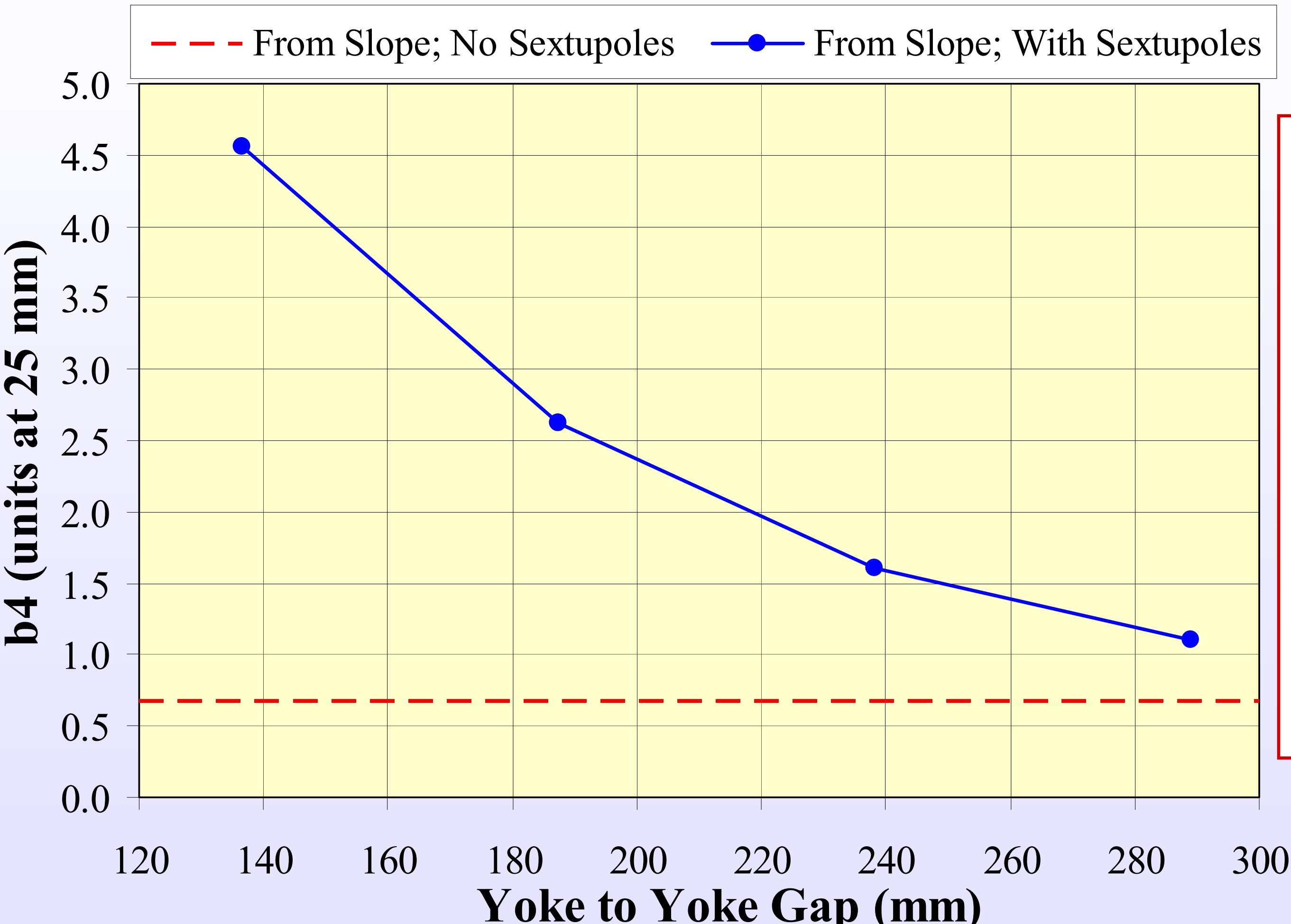


With sextupole

Distortion breaks 4-fold symmetry and creates octupole harmonic

SLS Quadrupole between Sextupoles

Measured Effect on the Normal Octupole Term (in Units)



- Octupole is a non-allowed harmonic in quadrupole.
- The presence of octupole is a clear indication of symmetry breaking.
- It is the most pronounced of all effects.

Courtesy: Animesh Jain (to be published)

Influence of

Nearby Hardware
(other than magnets)

on Field Quality

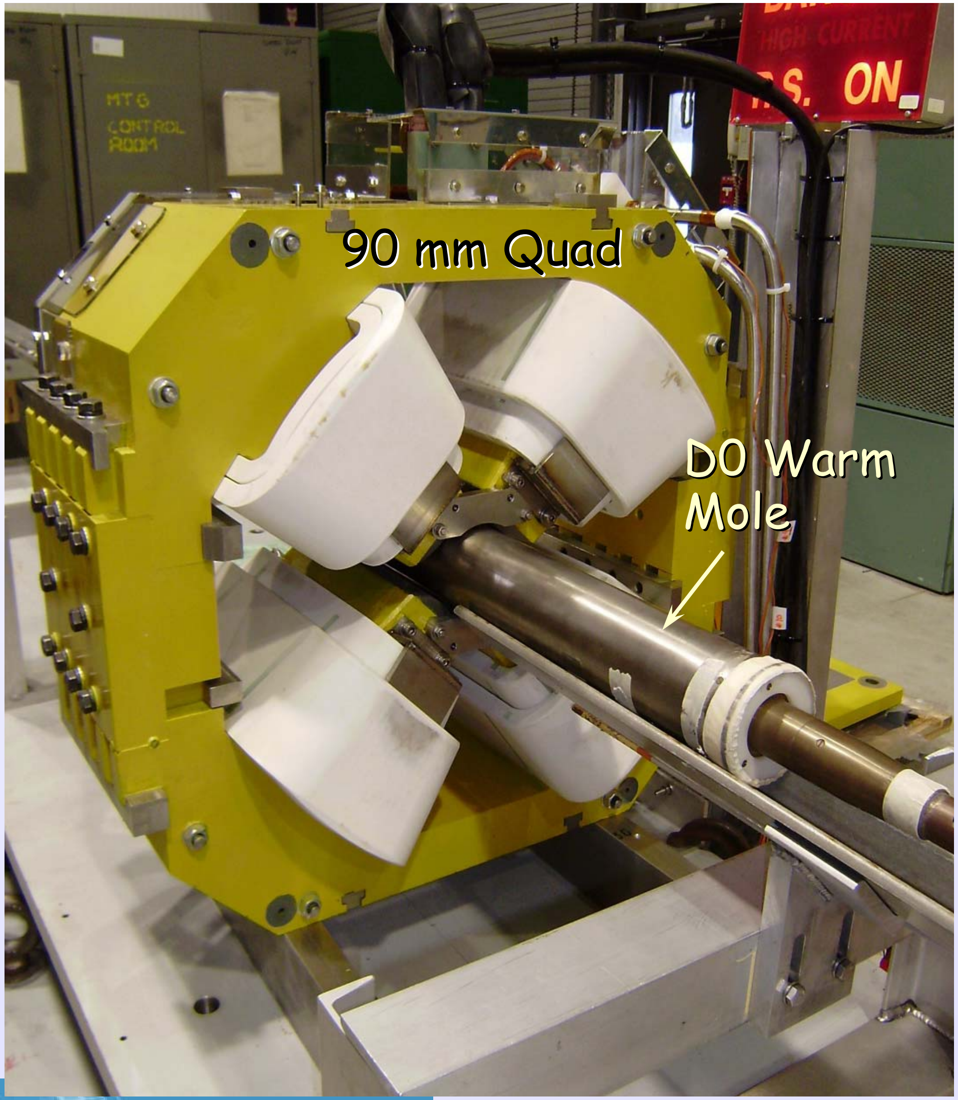
Configurations for Interaction Studies (for non-magnet hardware near the magnet)

Configurations Measured for IHEP 90 mm Quadrupole:

- Quadrupole on girder, with the nominal magnet height.
- Quadrupole with vacuum pump on girder.
- With vacuum pump and steel chamber support.
- With an invar sheet in place of the steel chamber support.

Courtesy: Animesh Jain

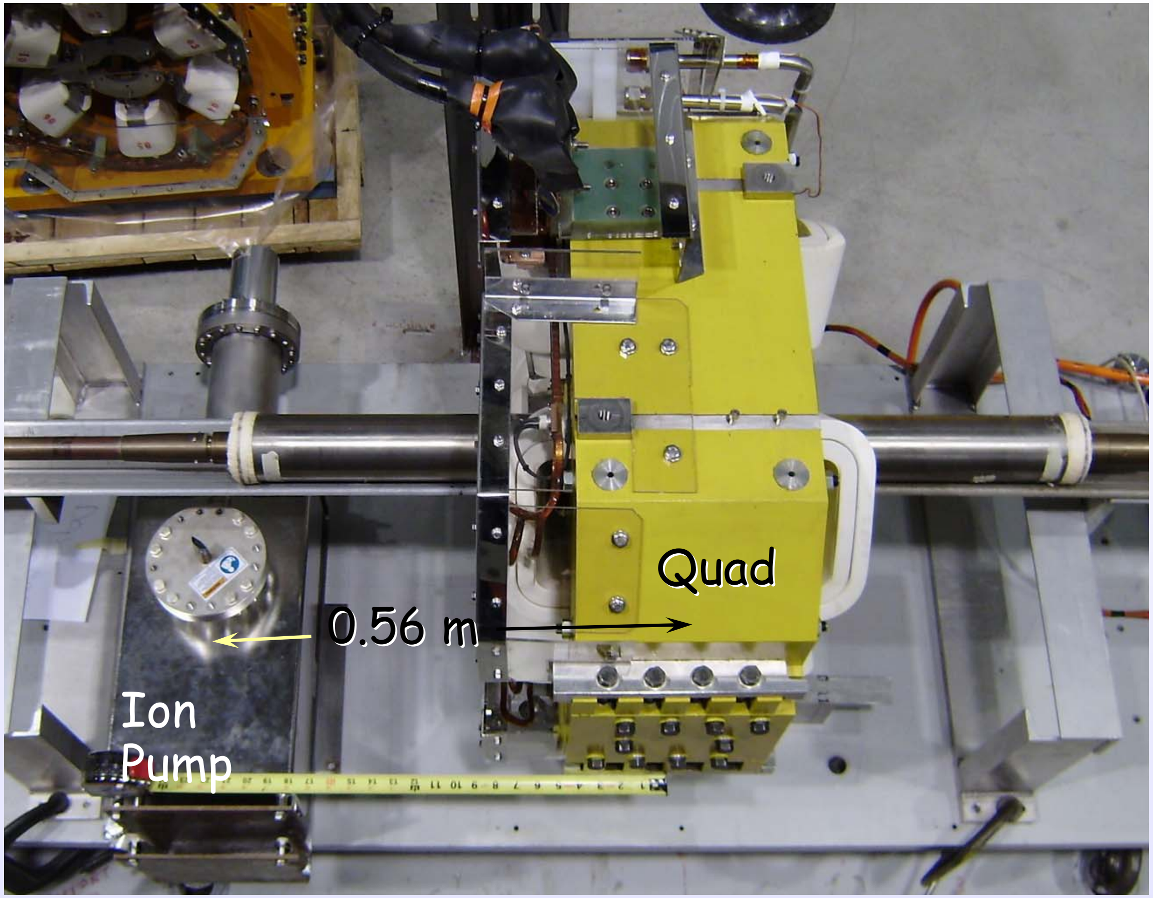
Influence of Girder



The magnet is supported on aluminum blocks on top of a girder prototype.

Courtesy: Animesh Jain (to be published)

Quadrupole with Vacuum Pump on the Girder



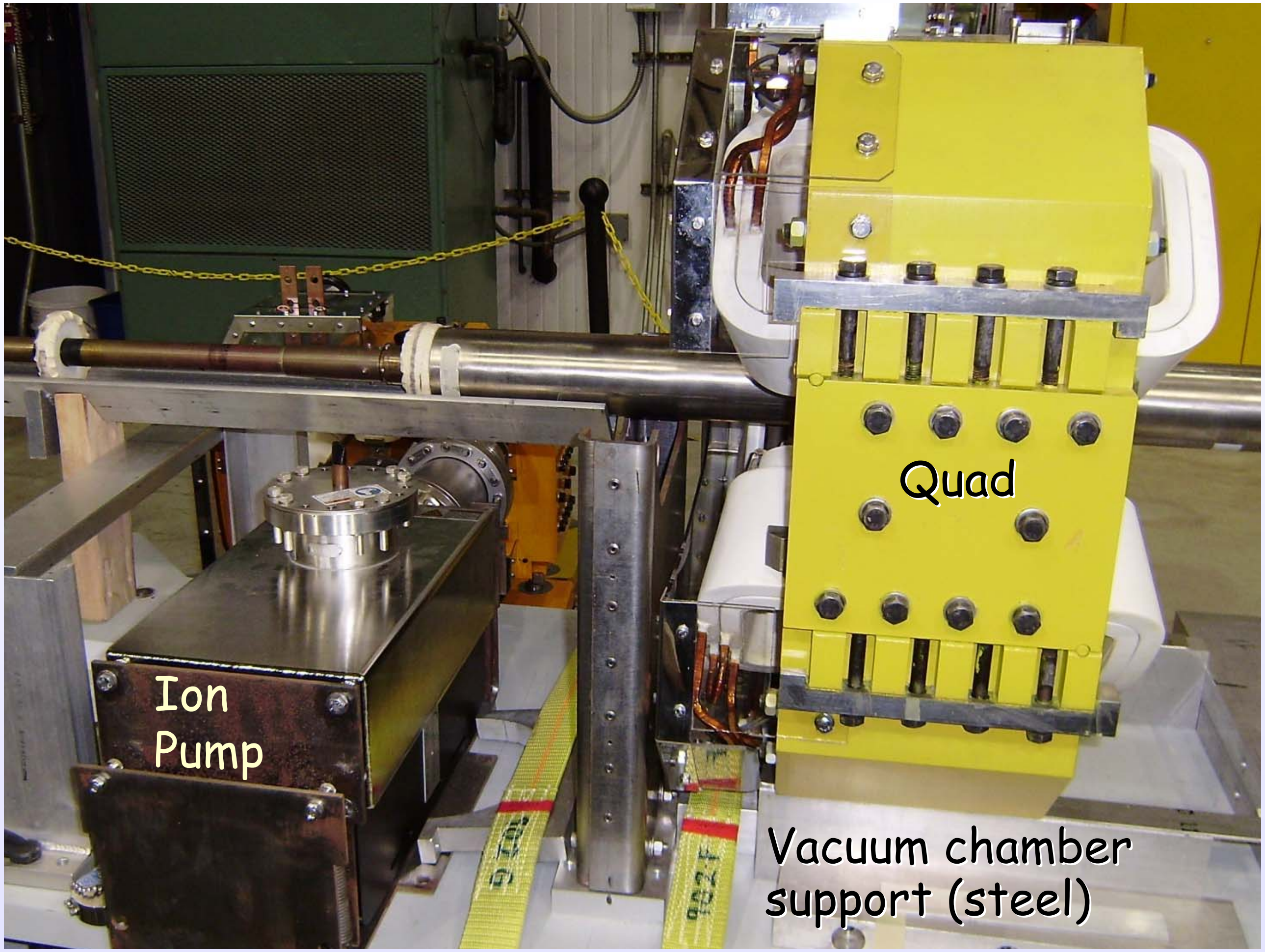
An ion pump is placed on the girder at ~0.56 m from quad center

Measuring coil may not pick up all field from the ion pump

But it does measure any influence on the quadrupole field quality

Courtesy: Animesh Jain (to be published)

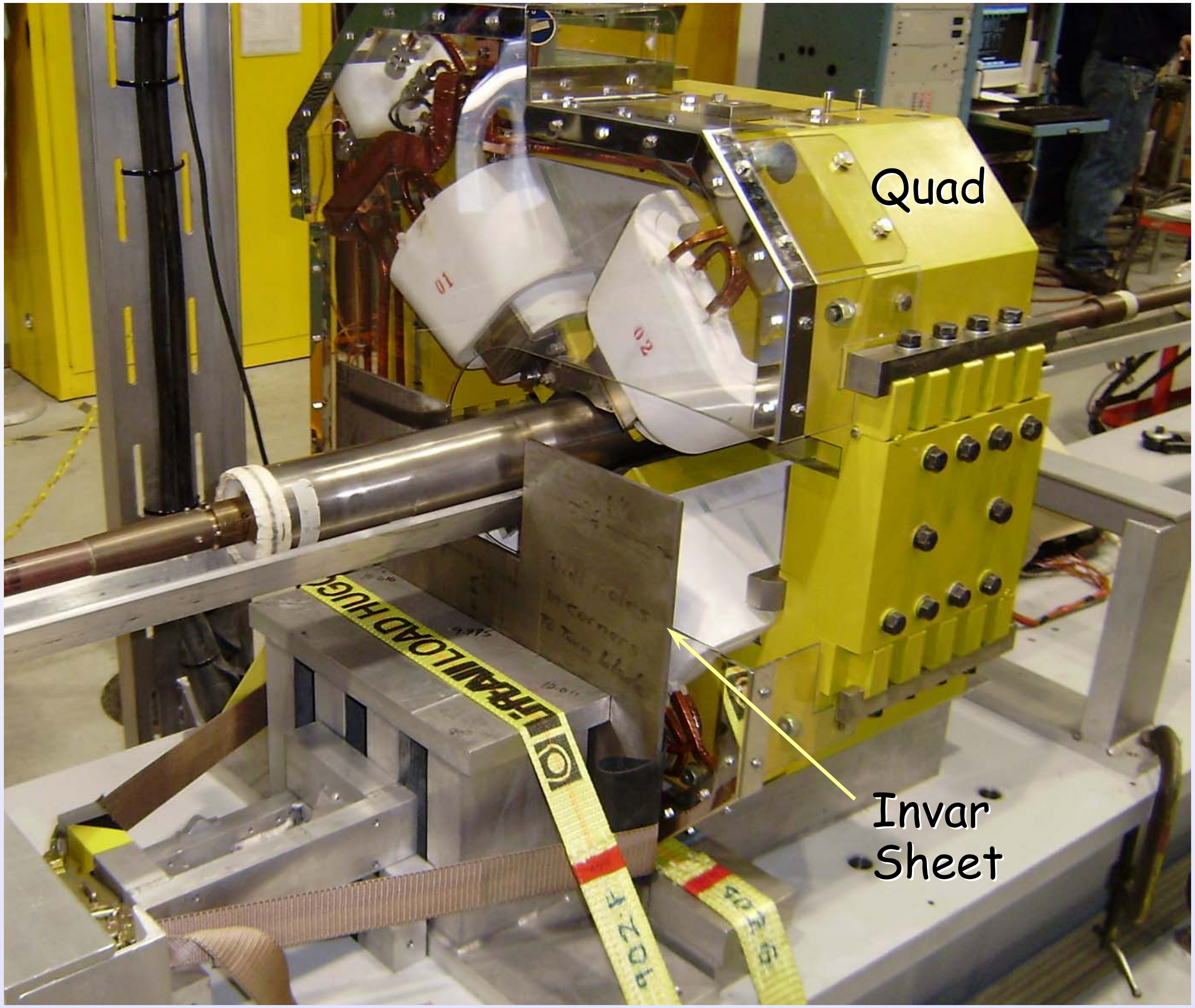
Vacuum Pump & Steel Chamber Support



Ion pump and a carbon steel mock up of the vacuum chamber support

Courtesy: Animesh Jain (to be published)

Vacuum Pump & Invart Sheet Simulating Support



A sheet of invar (instead of the steel vacuum chamber support) near the magnet.

Courtesy: Animesh Jain (to be published)

Summary of Interference Effects on Harmonics

Harmonics (@30 mm) in NSLQ06 (90 mm Quadrupole Prototype from IHEP)

Configuration	b3	b4	b5	b6	b7	a3	a4	a5	a6	a7
NSLS-II Specifications	**3.60**	**1.44**	**0.17**	**2.07**	**0.25**	**1.20**	**0.14**	**0.17**	**0.21**	**0.25**
No Base Plate (IHEP Data)	-2.01	-2.66	0.01	-1.76	-0.10	-1.05	0.23	-0.07	-0.04	-0.10
Quad on Girder	-2.40	-2.93	0.02	-1.69	-0.08	-1.33	0.11	-0.09	-0.04	-0.13
Quad with Ion Pump	-2.35	-2.85	0.01	-1.70	-0.08	-1.27	0.08	-0.11	-0.04	-0.13
Quad with Pump & Steel Support	**-3.72**	-2.74	**-0.26**	-1.82	-0.11	**-11.71**	**-0.59**	0.03	-0.12	-0.10
Quad with Invar Sheet	**-1.45**	**-5.61**	0.08	-1.95	-0.09	**-10.81**	0.26	**0.08**	-0.04	-0.04

Significant changes are highlighted

- This study identified a potential problem - one less surprise during commissioning.
- Use of alternate non-magnetic material and redesign of support are under investigation.

Courtesy: Animesh Jain (to be published)

Summary

• Low field, iron dominated magnet technology has been in existence for about half a century, however, there is always room for improvements. This presentation reported a number of significant developments.

• Introduction of nose piece in dipole magnets freed-up about 1.5% of real estate (which is significant), and provided additional benefits.

• Impressive progress has been made in alignment technique based on vibrating wire that should provide an absolute accuracy of ~ 5 microns.

• NSLS-II storage ring has a tightly packed lattice. Possible influence of nearby magnets and other materials has been systematically studied.

• With this knowledge and with significant advancement in technology during R&D phase, we are looking forward to a successful construction and commissioning of one of the most intense radiation sources.