Strategies to Assure/Tune Field Quality in EIC IR Cable Magnets (with B1pF as an example)

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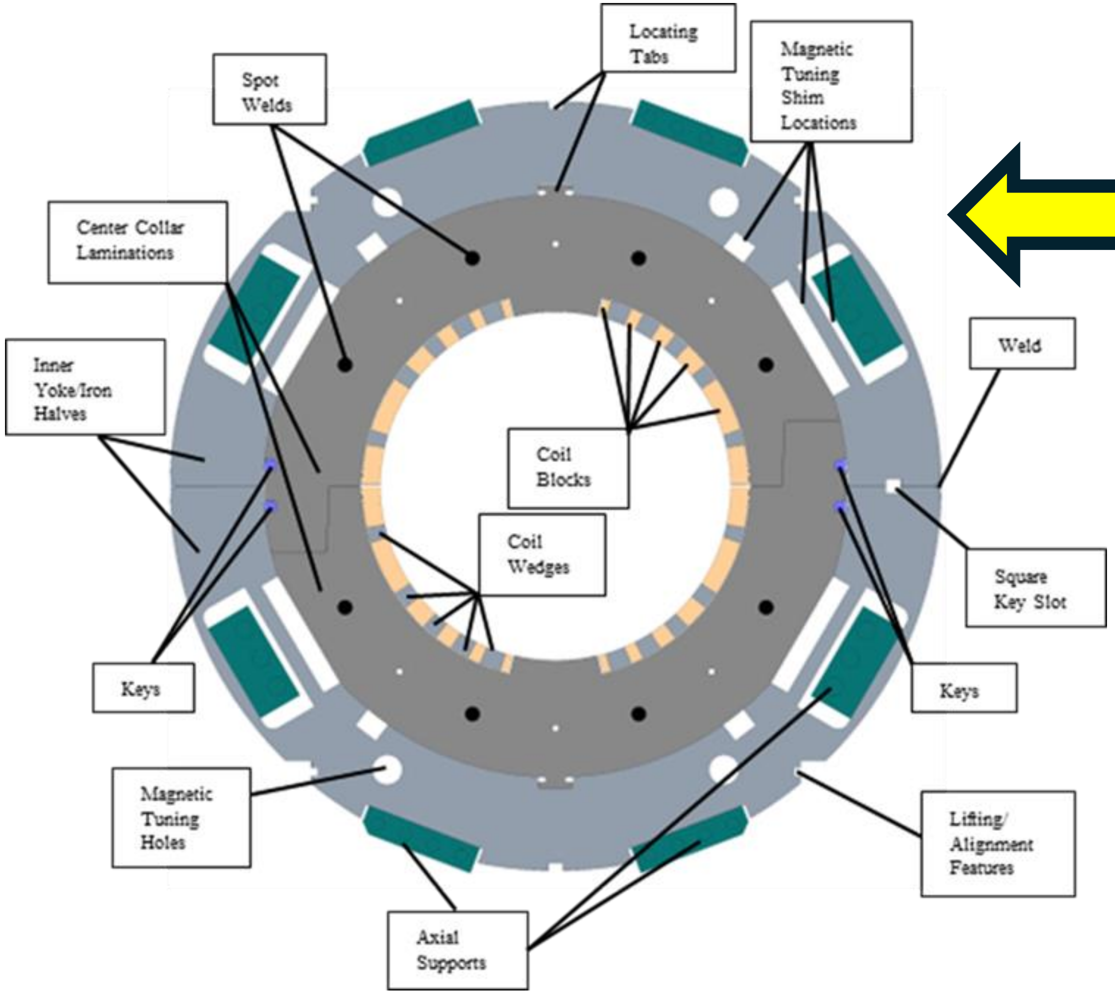
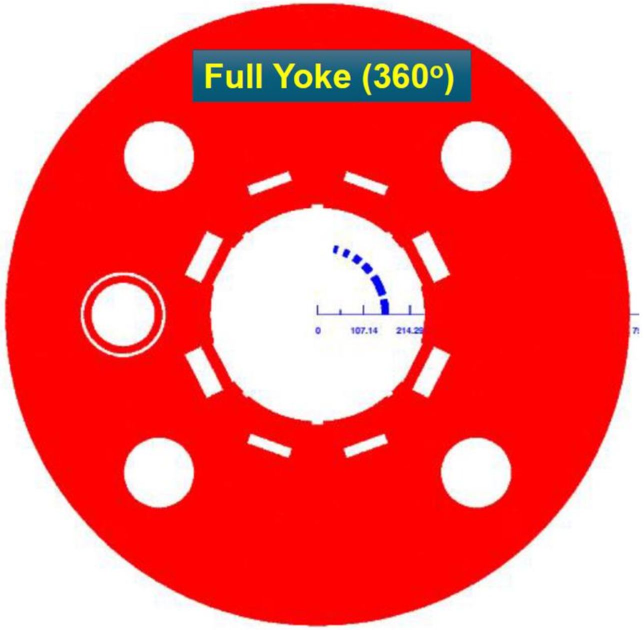
B1pF (with inner iron yoke ring)



<u>Assumptions</u>:

- Warm measurements and vertical cold test will be performed with the collared coil in the inner iron yoke (shown left).
- Horizontal cold test(s) will be performed with the outer yoke installed as well (shown below).



Strategies/steps developed and used in RHIC magnets to ensure good field quality and extended to EIC IR magnets (1)

➢ **B1pF as an example (steps can be generalized to other magnets)**

- Magnetic designs should be flexible enough to accommodate variations in parts. Impact of the error in parts (even if the error is within spec) could be significant.
- Inspect magnet parts (cable, wedges, collar, yoke), as delivered, and examine the impact of the deviations from the nominal (a report saying within spec not sufficient).
- Take advantage of the flexible design to adjust for the geometric errors. Check to ensure that enough room remaining to allow tuning of field the measured field quality
- Make warm measurements of harmonics of collared coil in iron ring. Adjust pole and midplane shims, in addition to the inner tuning shims, to correct both allowed and non-allowed harmonics, as necessary.
- Make warm measurements to ensure that harmonic changes were, as expected.

… continue

Strategies/steps developed and used in RHIC magnets to ensure good field quality and extended to EIC IR magnets (2)

… continuing from to the previous page (example B1pF)

- Measure field quality cold of the collared coil assembly in thin intermediate yoke in vertical Dewar at low currents to obtain geometric warm to cold correlation.
- Make adjustments in tuning shims close to collar (B1pF) and/or pole/midplane shims.
- Warm measurements again to ensure that the change in harmonics are as expected.
- Make cold horizontal measurements of the coil in full yoke. Energize the magnet over entire range of operation to obtain saturation or current dependence.
- Make adjustments in the outer tuning shims to improve field quality as a function of current. This step is to correct/adjust the current dependence at higher fields only.
- Make another cold horizontal measurement of fully cryo-stated magnet, if possible

✓ Experience of RHIC magnets will be used as examples.

Impact of non-nominal cable thickness (even within spec)

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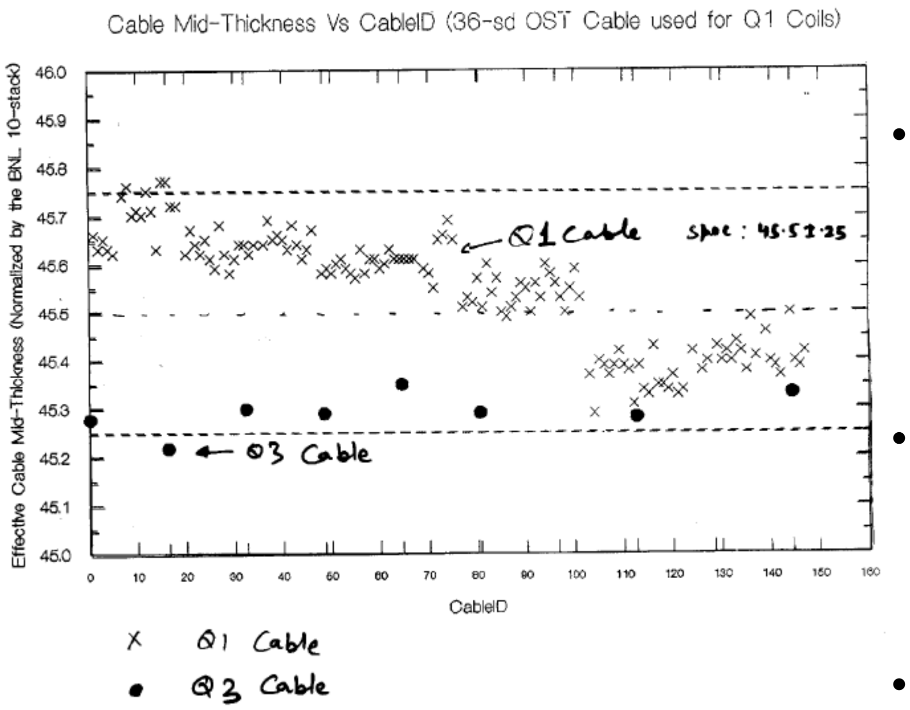
Different Size Cable (within spec) from Two Different Vendors

Specifications : +/- 0.25 mil (6.5 micron); 0.5 mil variation (13 micron)

Two vendors gave cable which differ systematically (but within specifications) by ~ 0.35 mil (however, had a small RMS)

27 turns => 9 mil (0.24 mm) much larger than desired.

A flexible design accommodated it!



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- **Cable size should be measured with nominal pre-stress. 10-stack measurements help.**
- **B1pF has 63 turns. A variation in cable thickness produces a variation in coil size. Even in spec (6 microns) deviation creates ~+/- 400 μm change in coil size.**
- **This can't be accommodated in curing. This is about an order of magnitude more than desired (+/- 25 μm). Impact on schedule of rejecting a slightly out of spec cable?**
- **Looking ahead with designs with a variation in wedge sizes (as in RHIC IR Quad) and/or fewer or more turns would help (DX ended up with extra turns).**
- **RHIC production went with good field quality magnets ahead (some with no prototype) as a lot was thought ahead and implemented seamlessly.**

Adjusting Geometric Harmonics & Pre-stress

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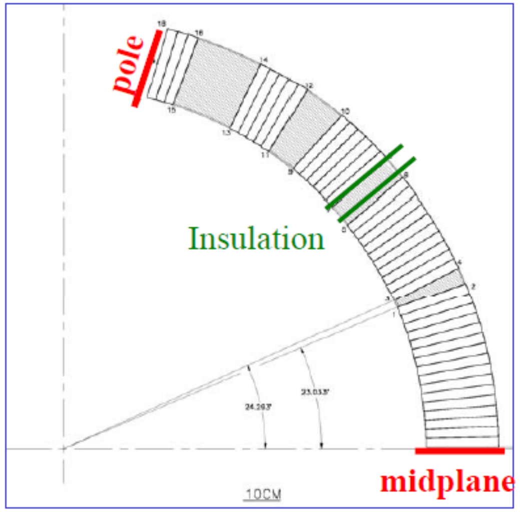
A Flexible Design from the Beginning

Design Philosophy:

- **Start out with a design that allows significant adjustability for field harmonics and mechanical parameters (cable thickness, wedges, etc.).**
- **A flexible design is generally economical, efficient and produces magnets with better performance. I think it's a prudent approach.**



Geometric: Start with a larger than required shim and midplane cap. Then adjust it, as required without changing the cross-section of the cured coil. One can also adjust the layers of wedge/cable insulation, if needed. These three parameters can adjust the first two allowed harmonics and pre-stress or cable insulation. This approach was used extensively in various RHIC magnets.

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- Coil-to-coil midplane gap in B1pF is > 2 mm (+/- 1 mm)
- Pole shims should be > 2 mm
- This will accommodate +/-0.4 mm in cable thickness for pre-stress. But field quality impact should also be examined.

- Compute the impact of errors in each and every part (whether the errors are within spec or out of spec).

Change in Harmonics for 0.1 mm Change in Dimension in D0 Dipole

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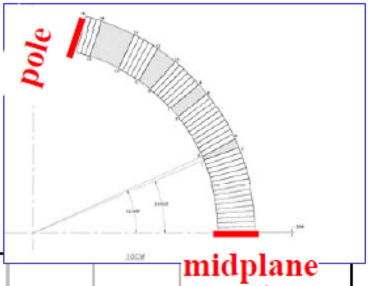
RHIC Insertion Dipole D0 with single layer coil

Coil inner radius = 100 mm,

Harmonic reference radius = 65 mm



"D0 MAGNET" : Rough Cross section Optimization Spread sheet

To iterate cross section for b2 & b4 with midplane and pole shims and fixed wedge changes, go to line b65:b72

Expected Parameters of the Iterated Design						b2	b4	b6	b8	b10	b12	b14	b16
Coil Prestress	1	mil from the target.	Expected Harmonic			6.23	2.24	0.54	0.240	-0.012	0.132	-0.047	-0.099
Coil Size						db2	db4	db6	db8	db10	db12	db14	db16
Target Increase	5	in Coil size	Mutliply	Change(mil)	Target b2n	-8.00	-2.30	-0.16	-0.15	0.016	-0.15	0.039	0.096
Total Increase	6	mil in compression				-1.77	-0.06	0.38	0.09	0.00	-0.02	-0.01	0.00
Midplane(mil)	1	Fixed Pole	0.25	4	-0.00333	-5.79	-1.85	-0.48	-0.16	-0.06	-0.02	-0.01	0.00
PoleShim(mil)	1	Decrease Pole	0.25	4	0.006	3.98	-0.53	0.09	-0.05	0.01	0.00	0.01	0.00
Wedge1(mil)	4	Fixed Pole	1	4	-0.0012	-1.32	0.53	0.48	0.14	0.02	-0.01	-0.01	0.00
Wedge2(mil)	0	Fixed Pole	0	4	0.00119	3.05	1.28	-0.06	-0.16	-0.01	0.02	0.01	0.00
Wedge3(mil)	0	Fixed Pole	0	4	0.00314	4.80	0.30	-0.37	0.02	0.03	-0.01	0.00	0.00
Wedge4(mil)	0	Fixed Pole	0	4	0.00508	4.89	-0.65	-0.01	0.04	-0.04	0.01	0.00	0.00
Midplane+4mil	0	Increase Pole	0	4	-0.0097	-9.76	-1.31	-0.57	-0.11	-0.07	-0.02	-0.02	0.00
Wedge1+4mil	0	Increase Pole	0	4	-0.00758	-5.28	1.06	0.389	0.187	0.006	-0.006	-0.013	0
Wedge2+4mil	0	Increase Pole	0	4	-0.0052	-0.91	1.81	-0.155	-0.117	-0.018	0.025	-0.002	0
Wedge3+4mil	0	Increase Pole	0	4	-0.00323	0.83	0.82	-0.462	0.067	0.023	-0.004	-0.006	0.004
Wedge4+4mil	0	Increase Pole	0	4	-0.0013	4.07	-1.37	0.439	-0.127	0.174	-0.184	-0.057	0

A simple spread-sheet like this helps in planning, rather than relying on the optimization programs like ROXIE, as we want to control the changes.

The goal here must be to minimize the mechanical changes to bring harmonics in acceptable range, rather than making them smallest possible.

Adjustments in midplane gaps and pole shims to correct both allowed and non-allowed harmonics

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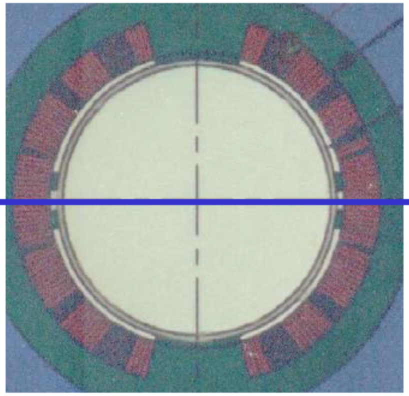
Change in Midplane Gap to Adjust Harmonics

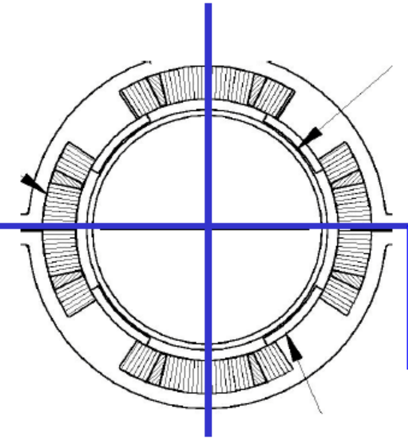
(can be easily done by changing the size of the ground-plane insulation cap)



Coil-to-coil midplane gap (1 in dipole)

Table 4.4.1: The computed and measured change in field harmonics at 25 mm reference radius due to a change in the coil midplane gap. The midplane gap was increased from 0.114 mm to 0.16 mm in the rebuilt 80 mm aperture RHIC model dipole magnet DRS009. In the production magnets, the midplane gap was changed back to 0.114 mm from 0.16 mm to adjust the b_4 harmonic.

	Δb_2	Δb_4	Δb_6	Δb_8
Computed	-3.0	-1.0	-0.28	-0.09
Measured	-3.0	-1.0	-0.29	-0.12



Coil-to-coil midplane gap (2 in quads)

Table 4.5.1: The measured and computed change in field harmonics caused by an asymmetric increase in the coil-to-midplane gap in the prototype 130 mm aperture RHIC interaction quadrupole QRI002. The gap was increased by 0.1 mm in the horizontal plane only. The harmonics are given at a reference radius of 40 mm.

	Δb_3	Δb_5	Δb_7	Δb_9
Computed	-6.8	-1.3	-0.45	-0.16
Measured	-6.5	-1.2	-0.30	-0.17

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- **An example of correction in non-allowed harmonics**
- **Also, an example of correction implemented wrong (trust but verify)**

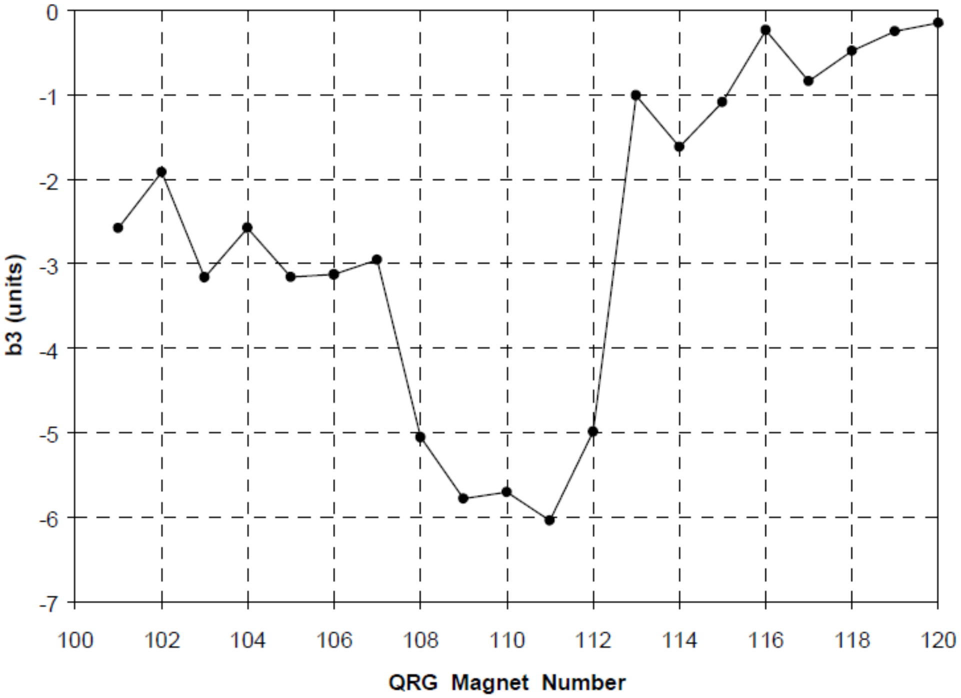
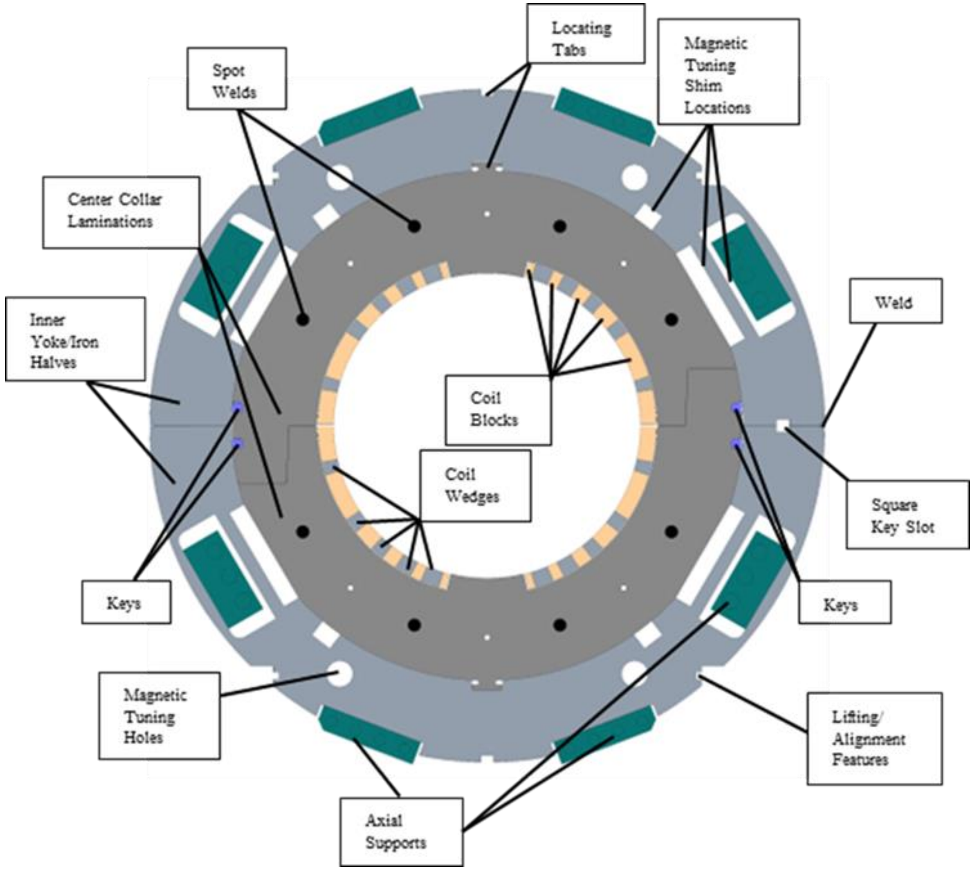


Figure 3: The measured octupole harmonic with the magnet number (first magnet named QRG101) in RHIC 80 mm aperture quadrupoles.

Step 1: Perform Warm Measurements and Make Correction

Correction based on the warm measurements

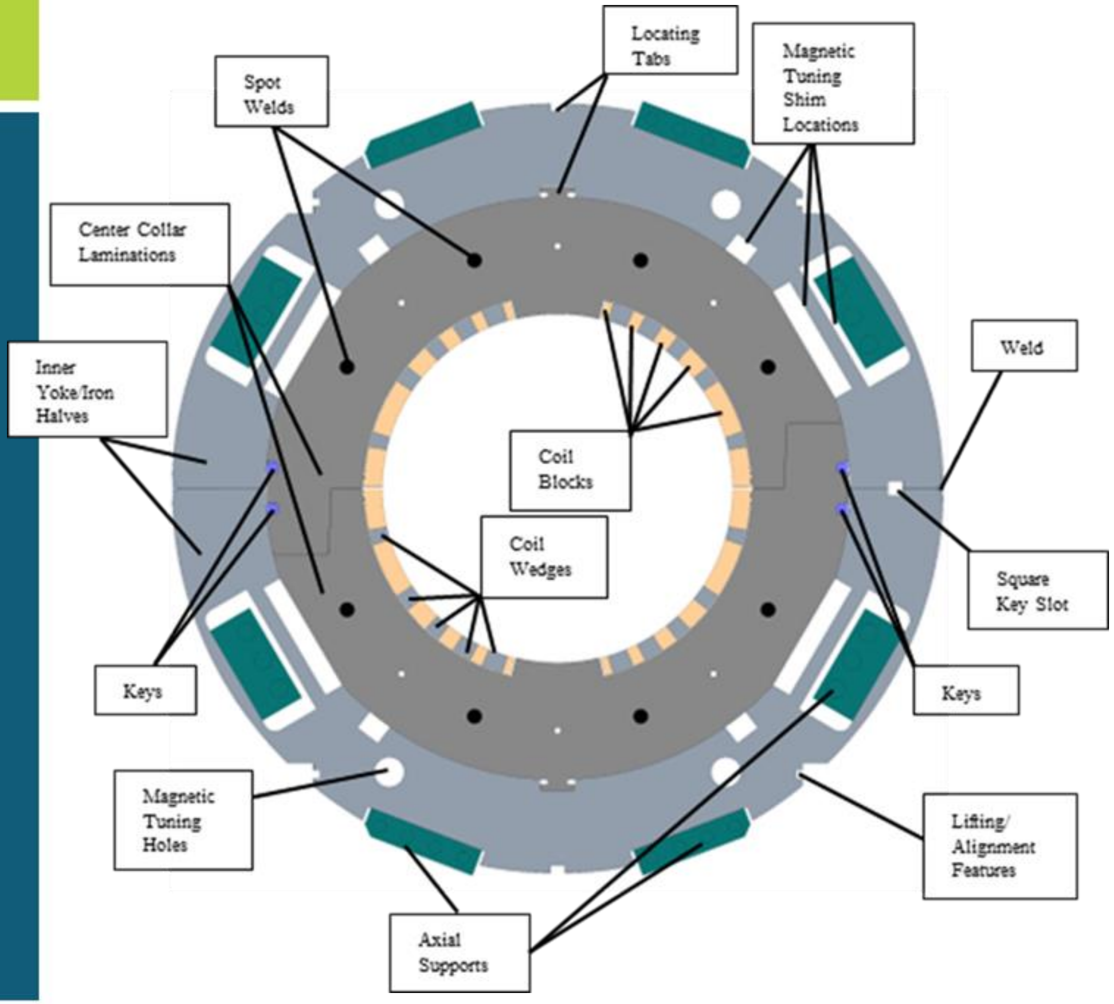


Eight tuning shims can correct up to max eight harmonics (four skew, four normal; two allowed, six non-allowed)

- Perform warm measurements of harmonics of the collared coil with inner iron.
- Compute the impact of errors in parts (even if the errors were within specifications).
- Make the adjustment to make harmonics small, whether the source is understood or not.
- Adjust the inner tuning shims, and in addition pole and midplane shims, if necessary, to correct both allowed and non-allowed harmonics.
- Make warm measurements to ensure that harmonic changes were, as computed and the differences are within the spec.
- If not, make one more correction and confirm with the warm measurements.

Step 2: Perform Cold Vertical Measurements and Make Correction

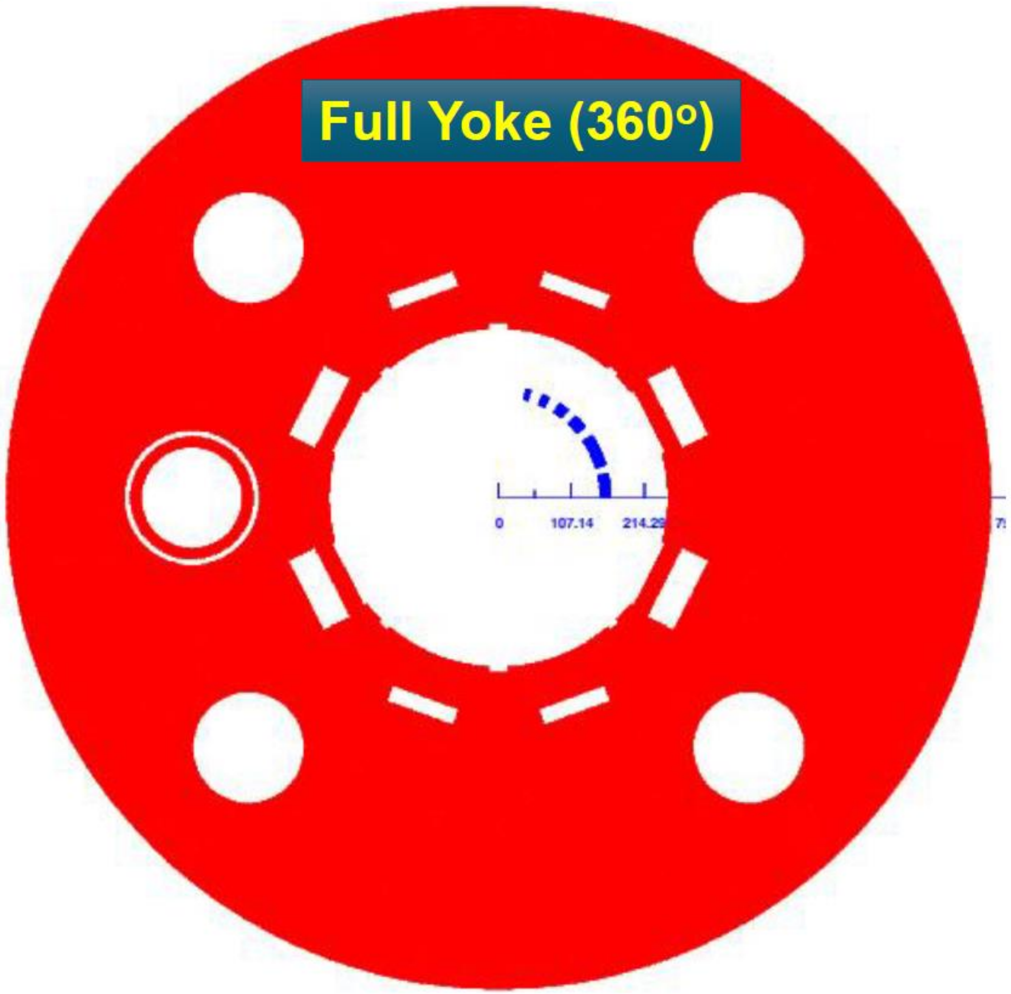
Correction based on the cold measurements



- Perform cold measurements of harmonics in vertical Dewar of the collared coil with inner iron. This test is to determine warm-to-cold change in low field (geometric) harmonics.
- Adjust the inner tuning shims (no change in pole or midplane shim), to make correction if the cold measurements take harmonics outside the specifications.
- Make warm measurements to ensure that harmonic changes were, as computed and the differences are within the specification (no need to do another cold measurement).
- If not, make one more correction and confirm with the warm measurements.

Step 3: Perform Cold Horizontal Measurements and Make Correction

Correction based on the cold measurements



- Perform cold measurements of harmonics with magnet placed horizontally at the test station with outer yoke installed over the inner iron.
- This test is to determine the change in harmonics as a function of current and to see if the harmonics at high fields needs to be corrected (it is assumed that the low field (geometric) harmonics are already corrected. This will also give a chance to verify again.
- Adjust the outer tuning shims (no change in the inner tuning shim), to make the correction.
- If possible, make another cold measurements to verify, after the full assembly of the magnet in cryostat ready to be sent to the machine.

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- Take advantage of the flexible design and adjust. Check to ensure that enough room is still remaining to allow further tuning of field quality after harmonic measurements
- Make warm measurements of harmonics of collared coil in iron ring. Adjust pole and midplane shims, in addition to the inner tuning shims, to correct both allowed and non-allowed harmonics, as necessary.
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Reference material on tuning field quality is available at: https://wpw.bnl.gov/rgupta/