



Magnetic Design

APUL D1 Dipole

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APUL CD2-CD3 DOE Review

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Overall Strategy for Assuring Good Field Quality

Many dipoles similar to APUL D1 - except for curvature (RHIC) or key material (US-LHC D1) - have been built. The only concern in field quality is the sextupole (b_3) harmonic. The following strategy will ensure the desired good field quality:

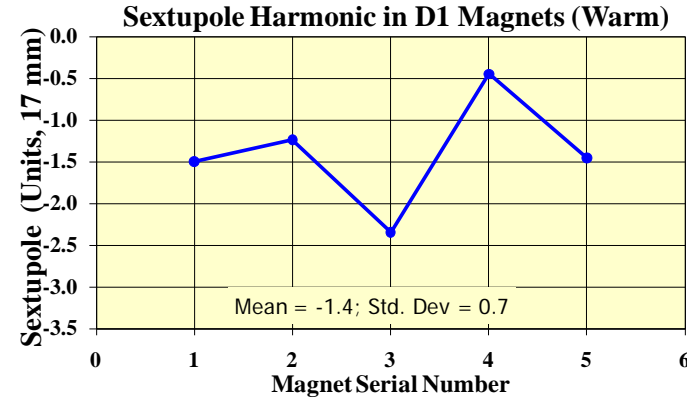
1. Measure field harmonics (warm) in the collared/yoked dipole.
2. Estimate field harmonics at various fields using the correlation of measurements at room temp and 4 K made on previous magnets.
3. Reduce geometric harmonics (nominal target: zero), if necessary, by adjusting pole shim and midplane-cap (previously developed technique).
4. Measure field quality cold after installing coldmass in cryostat.
5. Adjust saturation induced, if necessary, using a simple and relatively inexpensive technique that doesn't require cutting open the helium vessel.
6. The target for b_3 (@17 mm) : < 2 units at design field (~3.8 T @5.6 kA).



Correction of Geometric Field Harmonics

Design Philosophy:

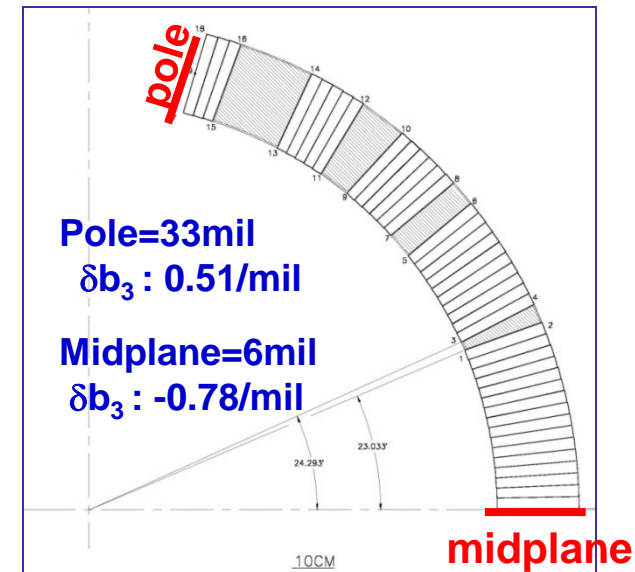
- Start out with a flexible design that allows significant adjustability in field harmonics.
- Develop a design with larger than minimum pole shim and midplane cap and then adjust, as needed.
- Measure warm harmonics in collared coil inside the iron yoke (yoke acts as a collar in APUL D1).
- Use warm-cold correlation to estimate geometric harmonics (at ~2 kA) and b_3 at the design field.
- If the expected harmonics are large, un-collar the coldmass, change the midplane and pole shims and measure harmonics again to verify the correction.
- This approach has been successfully used in many RHIC magnets. We will use it again in APUL D1 magnets. There is enough tuning range available.



Warm-Cold Correlation (RHIC):

$b_3(2\text{kA}) - b_3(\text{warm})$ @17 mm:

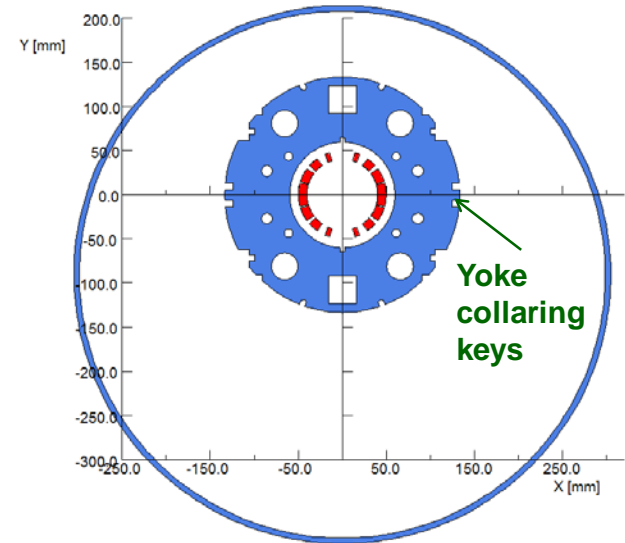
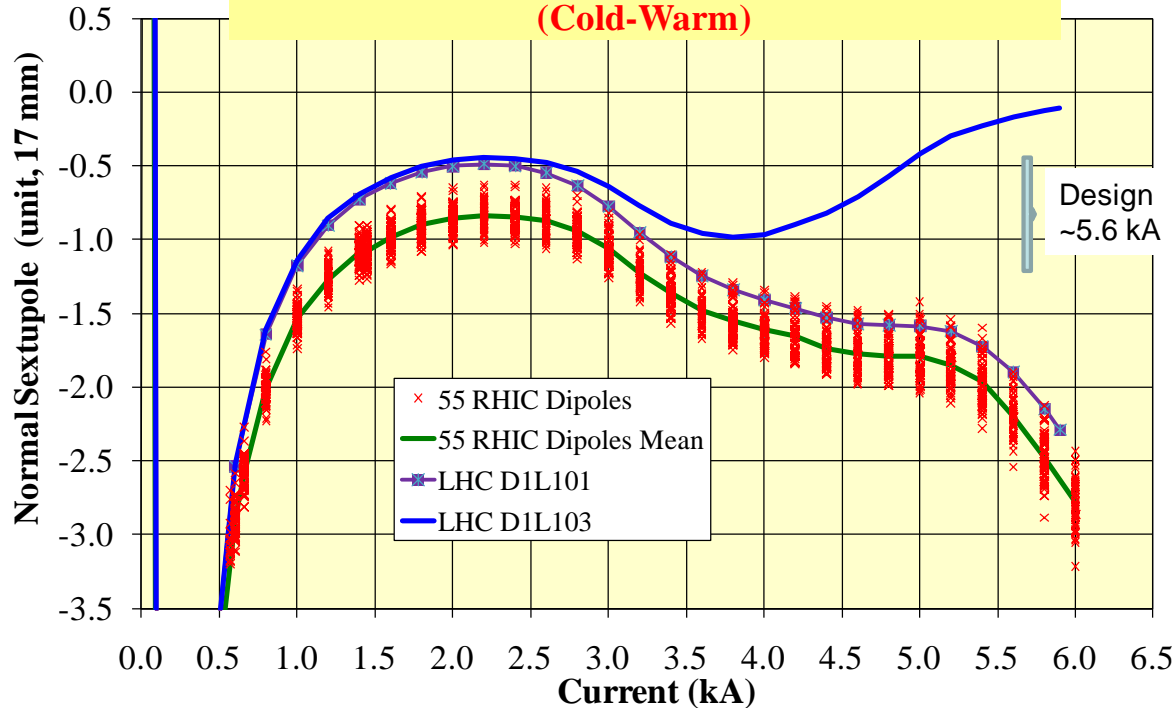
Mean = -0.86, std. dev. = 0.09





Saturation Induced Harmonics in RHIC and Previous LHC D1 Dipoles

Warm-Cold Offsets in D1L101, D1L103 & RHIC Dipoles (Cold-Warm)



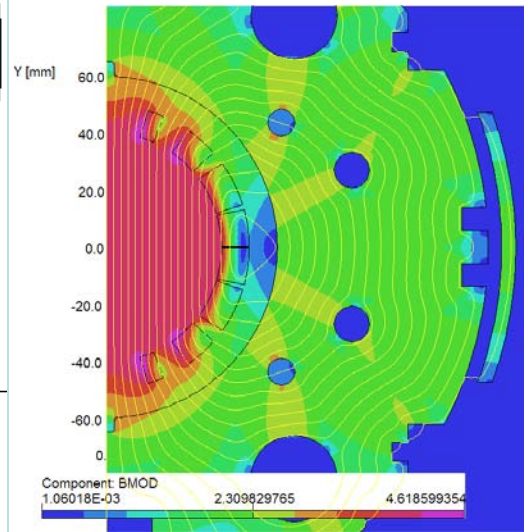
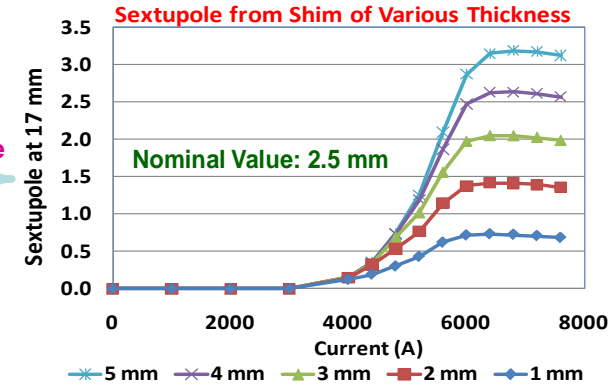
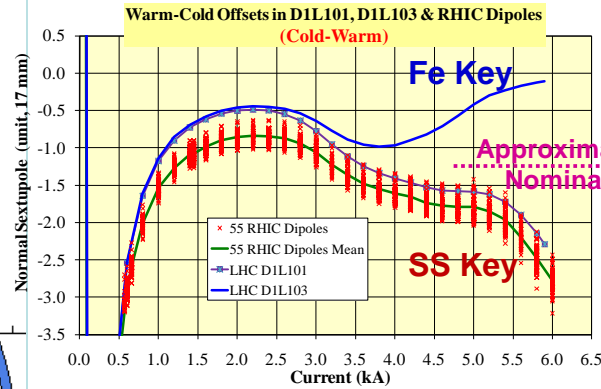
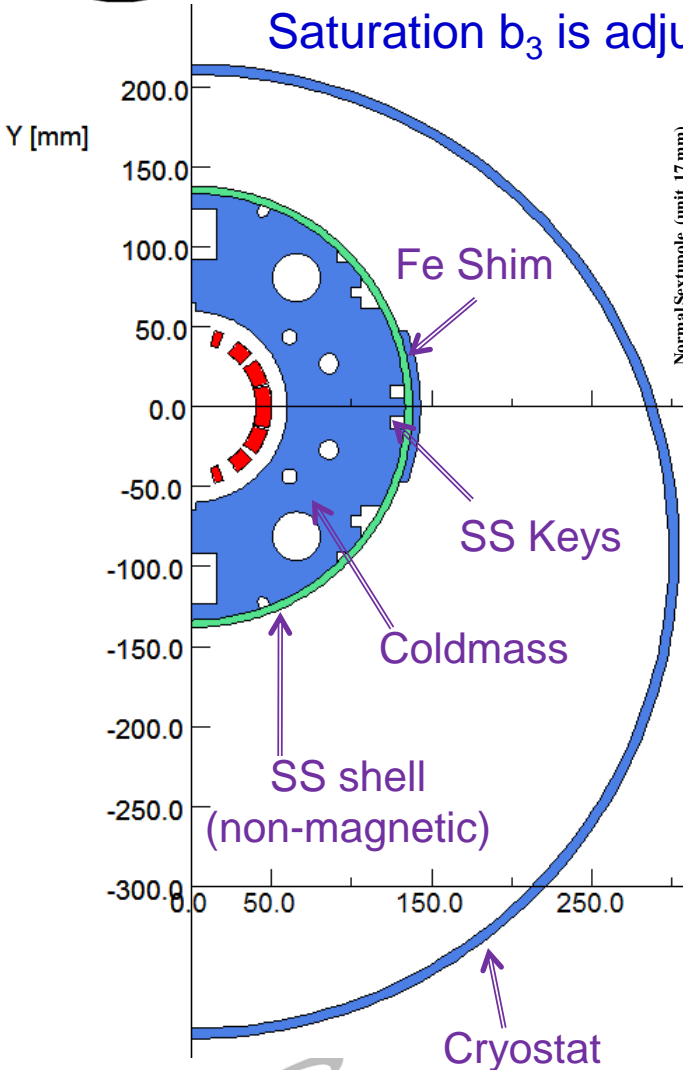
Note: One LHC dipole was (D1L101) made with SS (non-magnetic) keys and four with steel (magnetic) keys.

The ideal target will be to have zero nominal geometric b_3 (~2 kA) and zero saturation induced b_3 to design field (i.e. change between 2 kA and 5.6 kA). The ability to adjust saturation induced b_3 (similar to geometric) by ~1 unit will ensure good field quality.



Planned Method to Optimize and Adjust b_3 Saturation

Iron Shims on SS Shell: Nominal value gives zero change in b_3 at design field; none simulates SS key and full (5 mm thick and 100 mm wide) Fe key. Saturation b_3 is adjusted by adjusting shim thickness in 0.5 mm steps.



Simple, economical and yet powerful method to adjust saturation-induced harmonics in as built dipoles – no need to cut the weld of helium vessel, etc.



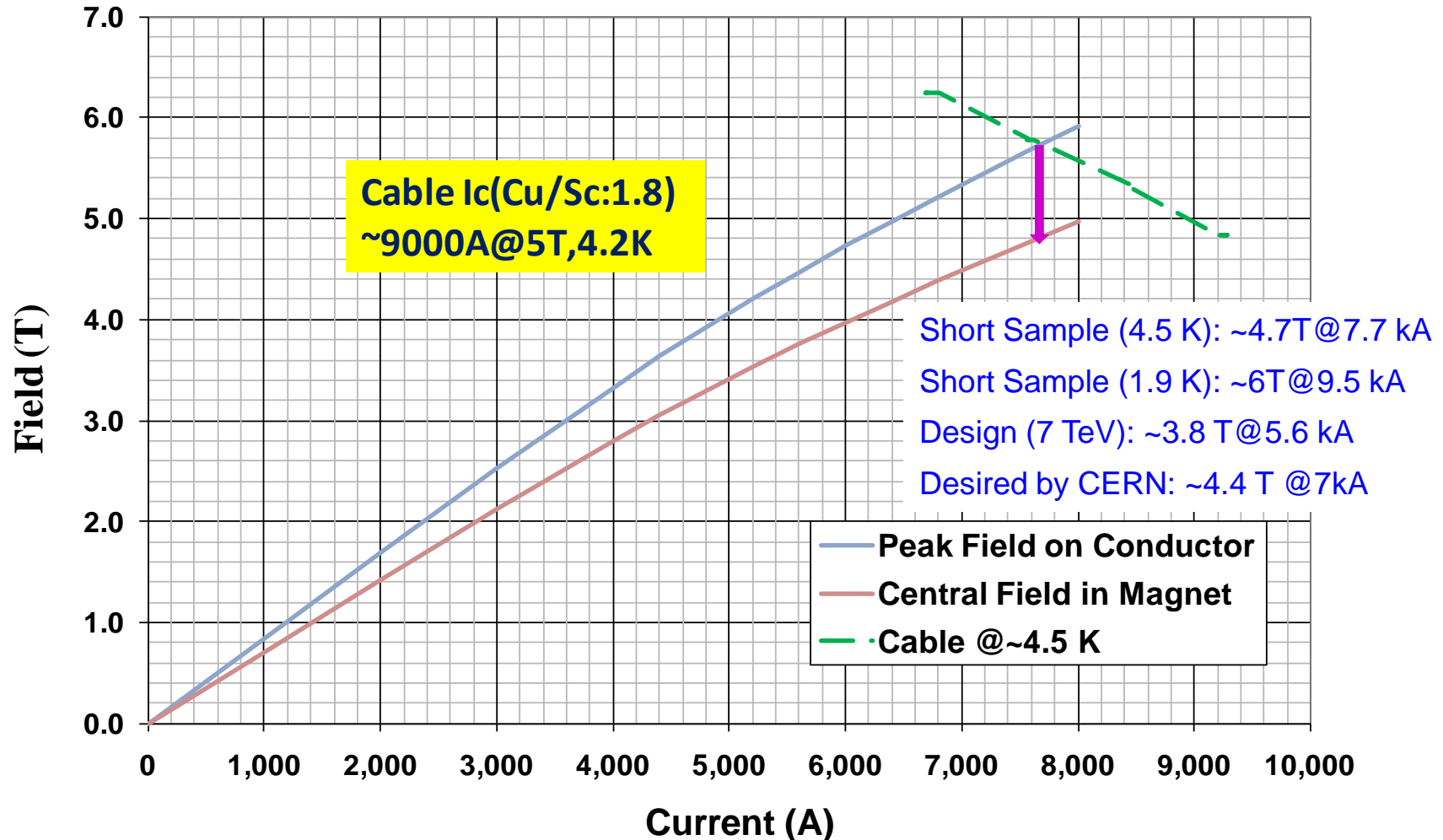
Detailed Strategy to Measure and Minimize b_3 at the Design Field with Iron Shims

1. Build coldmass 106 with 1/3 length full shim, 1/3 length half shim (nominal) and 1/3 length no shim. Do cold magnetic measurements with 1-meter long measuring coil. (The B-H curve of the shim is unknown. This measurement establishes the sensitivity of saturation b_3 to shim thickness.)
2. These measurements will provide (a) the nominal value of sextupole saturation (half shim) and (b) the change in saturation-induced sextupole (no shim, full shim).
3. Take coldmass 106 out of the cryostat, determine and install the optimized thickness of shim based on the above measurements, send to CERN.
4. Build coldmass 107 with the optimized shim. Do cold magnetic measurements. These will confirm the shim for both coldmasses.
5. If necessary, change the thickness of Fe shim placed outside the SS shell by taking coldmass out (no need to cut the weld of helium vessel, etc.).



Computed Quench Performance (Short Sample)

Computation of APUL D1 Short Sample @~4.5 K





Summary

- With this flexible design, we will be able to meet the APUL D1 field quality specifications. In particular, strategies have been developed to meet tighter specification of b_3 .
- We are adopting a value engineering approach (adjustments in magnets as built) to save on cost and schedule while assuring a good field quality.
- The first adjustment will be carried out after the warm measurements. It will be accomplished by adjusting the midplane and pole shims, if needed.
- The final adjustment will be made after the cold measurements. It will be accomplished by adjusting the thickness of the iron shims, as and if needed.
- These techniques assure that the field quality in these magnets will meet CERN specifications.



Back-up slides



Background

- In terms of field quality in APUL D1 dipoles, we should be ready to roll as the design is essentially the same as used in magnets that were delivered to CERN earlier. Moreover, except for a few minor differences, D1 dipoles are similar to RHIC dipoles.
- However, the present specification in the sextupole harmonic of <2 units @17 mm at the design field (~ 3.8 T @ ~ 5.6 KA for 7 TeV) was not met in two of the five magnets (including one spare) delivered.
- Moreover, the normal construction tolerances (due to wedges and other parts) could generate a cumulative error in sextupole beyond the above specification.
- In addition, the magnetic properties of yoke steel and geometry of lamination may be slightly different (still within tolerances). This could make the saturation induced sextupole harmonic slightly different from previous construction.
- To overcome above challenges, a flexible design philosophy is being adapted to allow minor adjustments (if necessary) to ensure that both magnets meet the specifications.
- Such approaches overcome the normal statistical harmonic errors. They have been previously applied successfully in RHIC magnets. They should work again here.



Summary of Integral field quality in D1 dipoles at 350A, Up ramp, 4.5 K

All data extrapolated to 4.5 K from warm measurements (except D1L101 and 103)

Actual operating temperature is 1.9K, which will impact the sextupole at injection significantly

All harmonics are in units of 1E-4 at a reference radius of 25 mm. (January 27, 2004 version)

	101_350	102_350	103_350	104_350	105_350	Mean_350	Sigma_350
ITF (T.m/kA)	6.668	6.668	6.662	6.668	6.666	6.667	0.04%
MagLen (m)	9.425	9.416	9.414	9.415	9.415	9.417	0.05%
FldAng (mrad)	-0.5	-1.2	-1.1	-0.8	-0.6	-0.8	0.3
b2	-0.49	-0.57	-0.18	-0.16	0.75	-0.13	0.52
b3	-14.86	-14.50	-16.89	-12.78	-14.96	-14.80	1.46
b4	-0.07	0.28	0.00	0.28	0.29	0.16	0.18
b5	0.38	0.48	0.29	0.68	0.59	0.49	0.16
b6	-0.02	0.01	-0.02	0.08	0.12	0.03	0.06
b7	-0.41	-0.49	-0.50	-0.40	-0.36	-0.43	0.06
b8	0.01	-0.04	0.01	-0.05	-0.01	-0.02	0.02
b9	-0.01	0.03	-0.04	0.05	0.05	0.02	0.04
b10	0.05	0.04	0.00	0.03	0.05	0.03	0.02
b11	-0.73	-0.74	-0.75	-0.76	-0.74	-0.74	0.01
a2	-0.12	2.17	-2.04	-1.54	-4.04	-1.11	2.31
a3	-0.92	-0.94	-0.71	-0.84	-0.90	-0.86	0.09
a4	-1.02	0.07	0.46	0.34	-0.45	-0.12	0.61
a5	0.21	0.07	0.28	0.07	0.22	0.17	0.10
a6	0.06	-0.08	0.11	0.34	0.08	0.10	0.15
a7	-0.09	-0.12	-0.07	-0.09	-0.14	-0.10	0.03
a8	0.02	0.00	0.07	0.05	0.01	0.03	0.03
a9	0.02	0.02	0.04	0.00	0.00	0.02	0.02
a10	0.05	0.07	0.05	0.09	0.07	0.07	0.02
a11	-0.01	-0.02	0.00	-0.01	-0.01	-0.01	0.01



Summary of Integral field quality in D1 dipoles at 5600A, Up ramp, 4.5 K

All data extrapolated to 4.5 K from warm measurements (except D1L101 and 103)

Actual operating temperature is 1.9K

All harmonics are in units of 1E-4 at a reference radius of 25 mm. (January 27, 2004 version)

	101_5600	102_5600	103_5600	104_5600	105_5600	Mean_5600	Sigma_5600
ITF (T.m/kA)	6.314	6.327	6.322	6.327	6.325	6.323	0.09%
MagLen (m)	9.439	9.431	9.430	9.431	9.430	9.432	0.04%
FldAng (mrad)	-0.5	-1.2	-1.1	-0.8	-0.6	-0.8	0.3
b2	-0.58	-0.62	-0.23	-0.22	0.70	-0.19	0.53
b3	-6.06	-2.08	-4.47	-0.37	-2.55	-3.10	2.20
b4	-0.09	0.27	-0.02	0.26	0.28	0.14	0.18
b5	0.38	1.11	0.92	1.31	1.22	0.99	0.37
b6	-0.08	0.02	0.00	0.10	0.14	0.03	0.08
b7	1.10	1.11	1.11	1.21	1.25	1.16	0.07
b8	0.01	-0.03	0.01	-0.03	0.00	-0.01	0.02
b9	-0.10	-0.06	-0.12	-0.05	-0.04	-0.07	0.03
b10	0.05	0.05	0.00	0.03	0.05	0.04	0.02
b11	-0.66	-0.68	-0.68	-0.70	-0.68	-0.68	0.01
a2	-2.37	0.18	-4.04	-3.53	-6.04	-3.16	2.29
a3	-0.90	-0.90	-0.68	-0.81	-0.86	-0.83	0.09
a4	-1.49	-0.39	0.00	-0.11	-0.90	-0.58	0.62
a5	0.23	0.07	0.28	0.07	0.22	0.17	0.10
a6	-0.05	-0.12	0.06	0.30	0.04	0.05	0.16
a7	-0.10	-0.12	-0.07	-0.10	-0.14	-0.11	0.03
a8	0.03	0.02	0.08	0.07	0.03	0.05	0.03
a9	0.03	0.02	0.04	0.00	0.01	0.02	0.02
a10	0.04	0.06	0.05	0.09	0.06	0.06	0.02
a11	-0.01	-0.02	0.00	-0.01	-0.01	-0.01	0.01

BROOKHAVEN Courtesy: Animesh Jain

NATIONAL LABORATORY

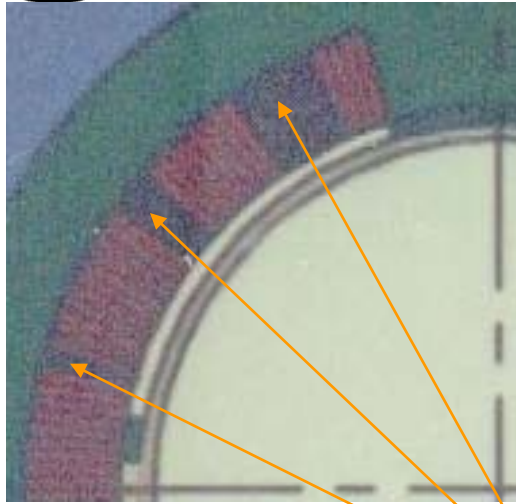


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Geometric Field Errors in 80 mm Dipole from 25 micron (1 mil) error in Component



Wedges

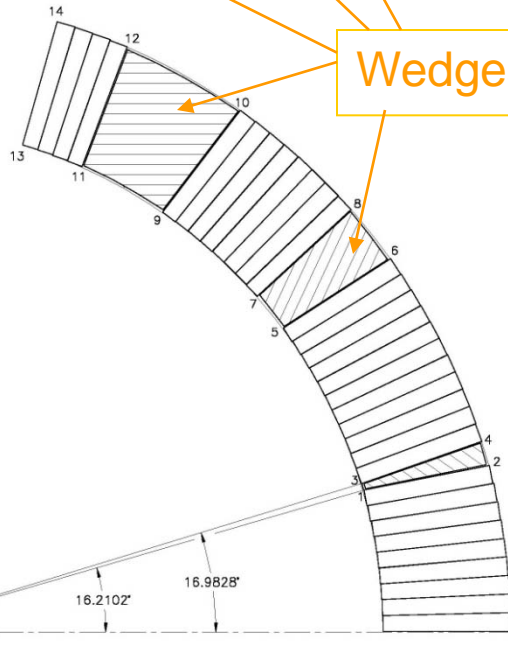


Table 4.3.2: The computed change in the transfer function and field harmonics produced by a $+25\mu\text{m}$ ($0.001''$) change in the wedge thickness, pole width or midplane gap in the RHIC 80 mm aperture arc dipoles. The field harmonics are calculated with a 25 mm reference radius. The numbering of the wedges starts at the midplane. The pole width and midplane gap are measured from the vertical and horizontal axis, respectively.

(coil radius = 40 mm, reference radius = 25 mm)

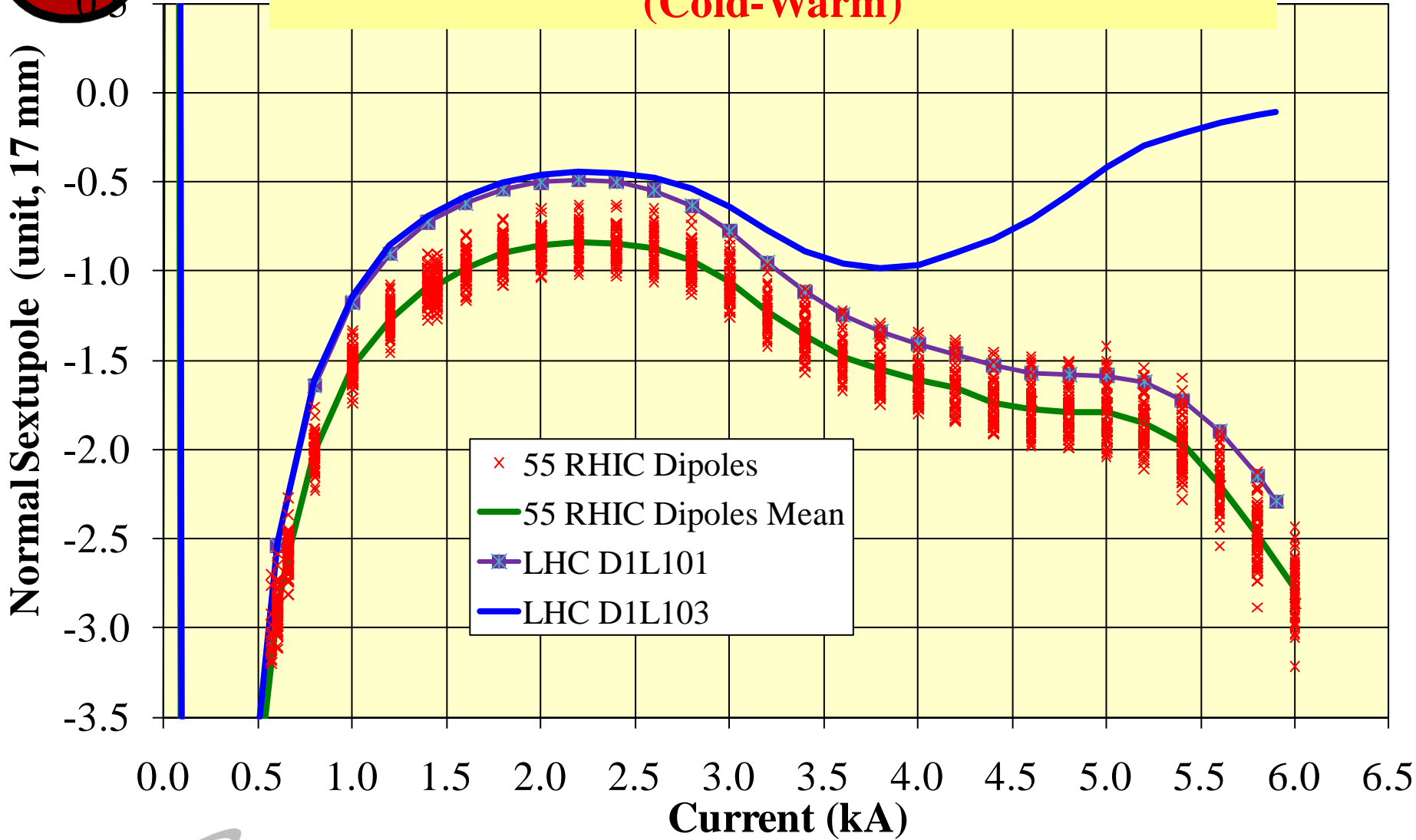
Parameter	δTF	δb_2	δb_4	δb_6	δb_8
changed	$10^{-4} \frac{T}{kA}$	10^{-4}	10^{-4}	10^{-4}	10^{-4}
Wedge 1	-0.6	-0.98	-0.122	0.061	0.043
Wedge 2	0.1	0.69	0.423	0.022	-0.050
Wedge 3	1.1	1.42	-0.090	-0.068	0.041
Pole Width	1.7	1.11	-0.154	0.039	-0.014
Midplane Gap	-0.9	-1.68	-0.557	-0.156	-0.050

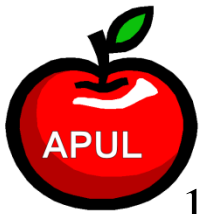
In above table b_2 is sextupole (US) - most places b_3 is used.
@17 mm reference radius, sextupole is $< 1/2$ (~ 0.46) of above

Cumulative b_3 in the first magnet test due to above 25 μm errors and other assembly errors could be > 2 units @17mm.
Proposed strategies would bring it < 2 units after adjustments.

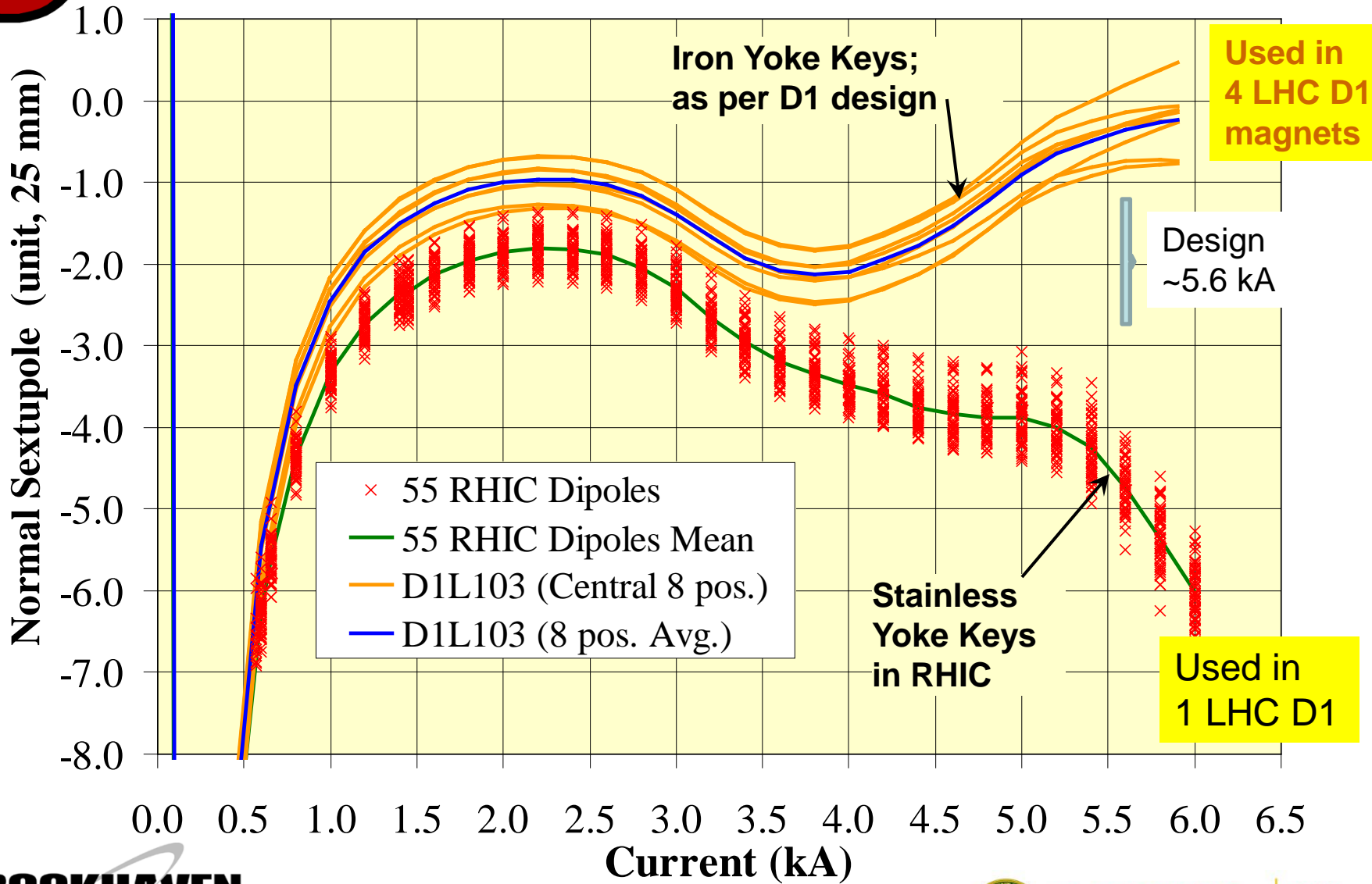


Warm-Cold Offsets in D1L101, D1L103 & RHIC Dipoles (Cold-Warm)





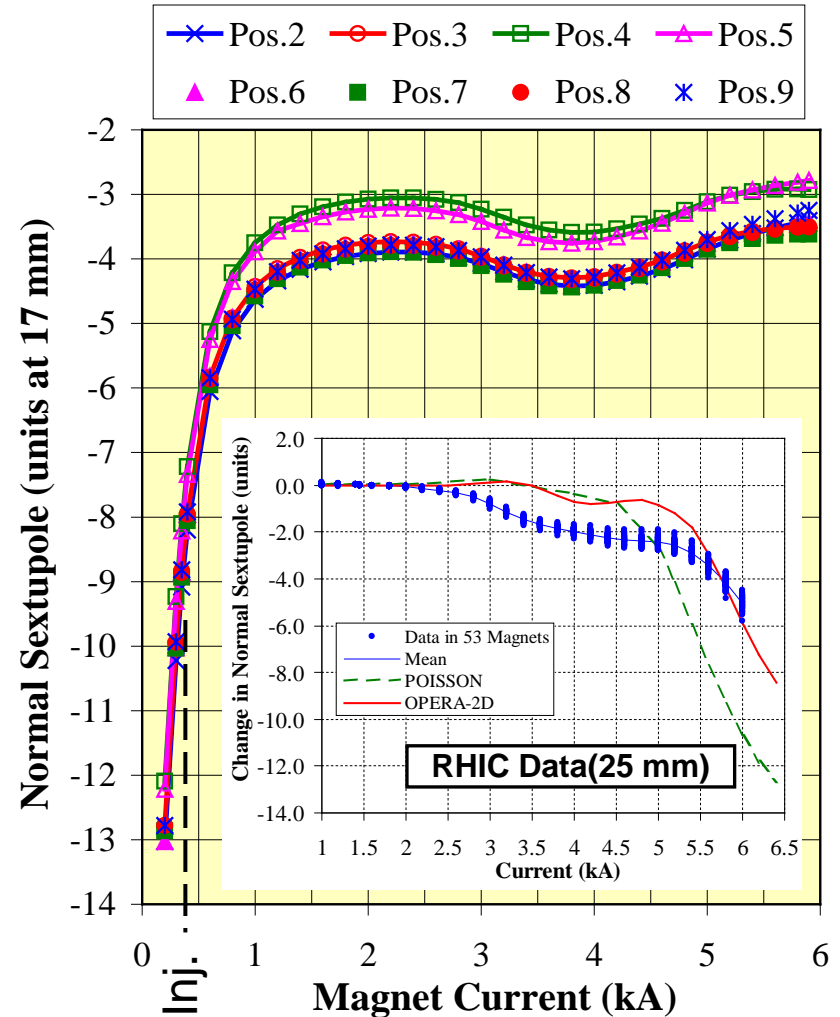
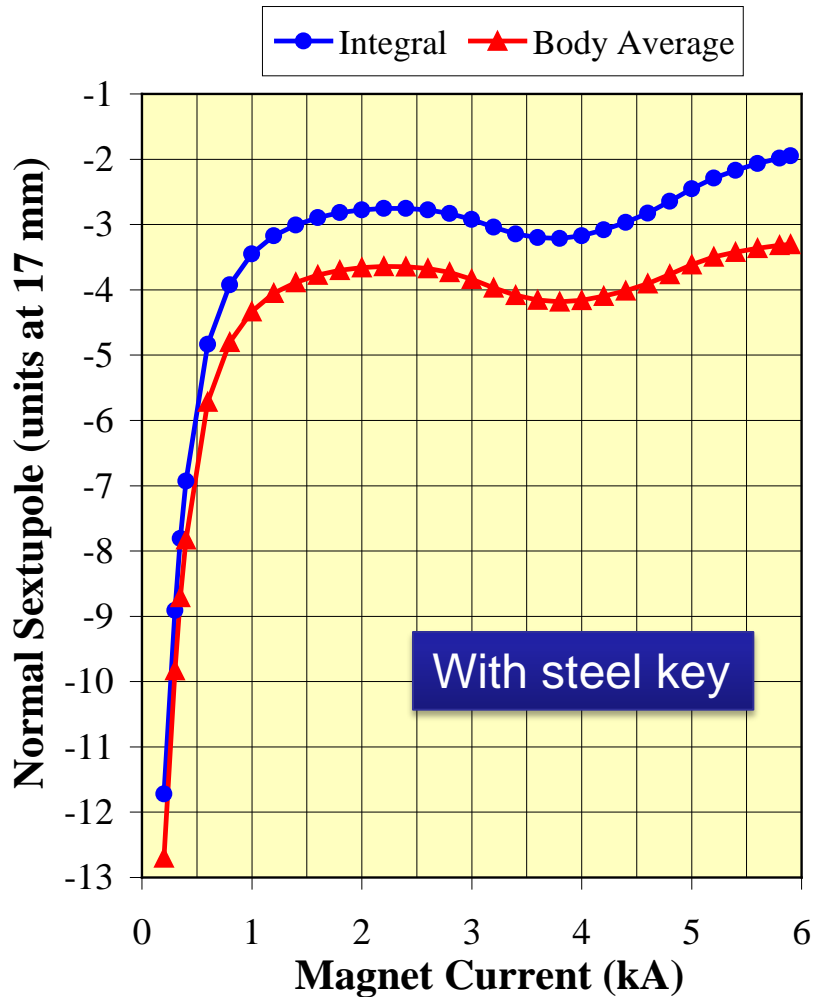
Warm-Cold Offsets in D1L103 & RHIC Dipoles





Excitation Curves (D1L103)

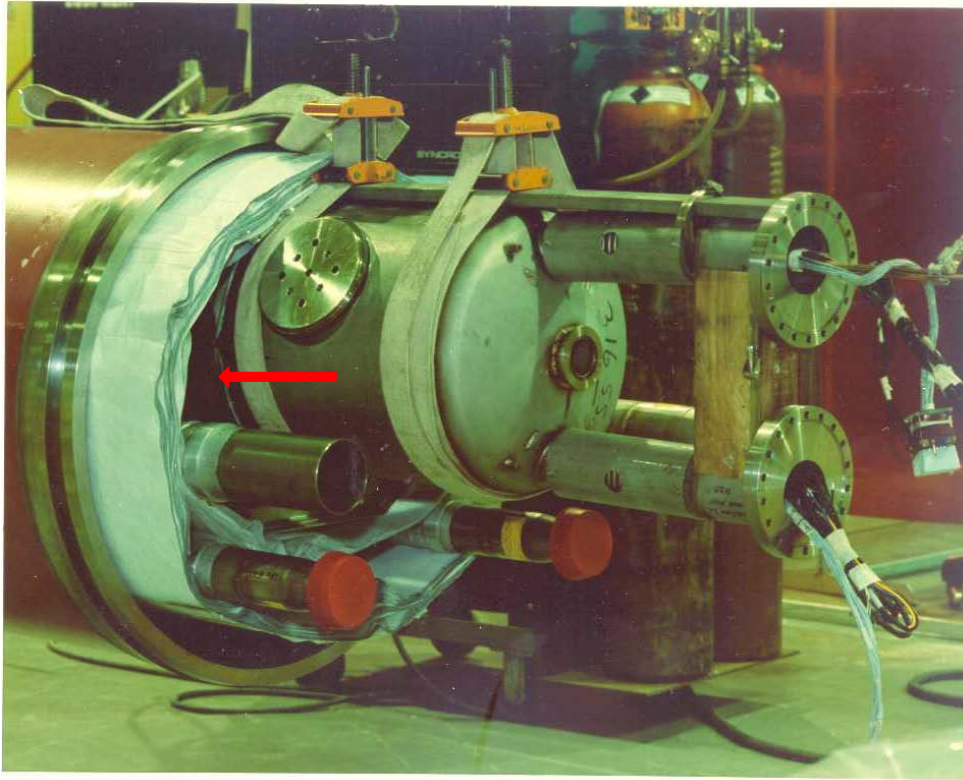
Integral, Body and 1 meter Interval





Simple Method to Adjust Saturation of as-built Magnets

Installation of Saturation Control Iron Shims on SS Shell
(earlier method required cutting the weld to insert rods to adjust saturation control rods, this one does not)



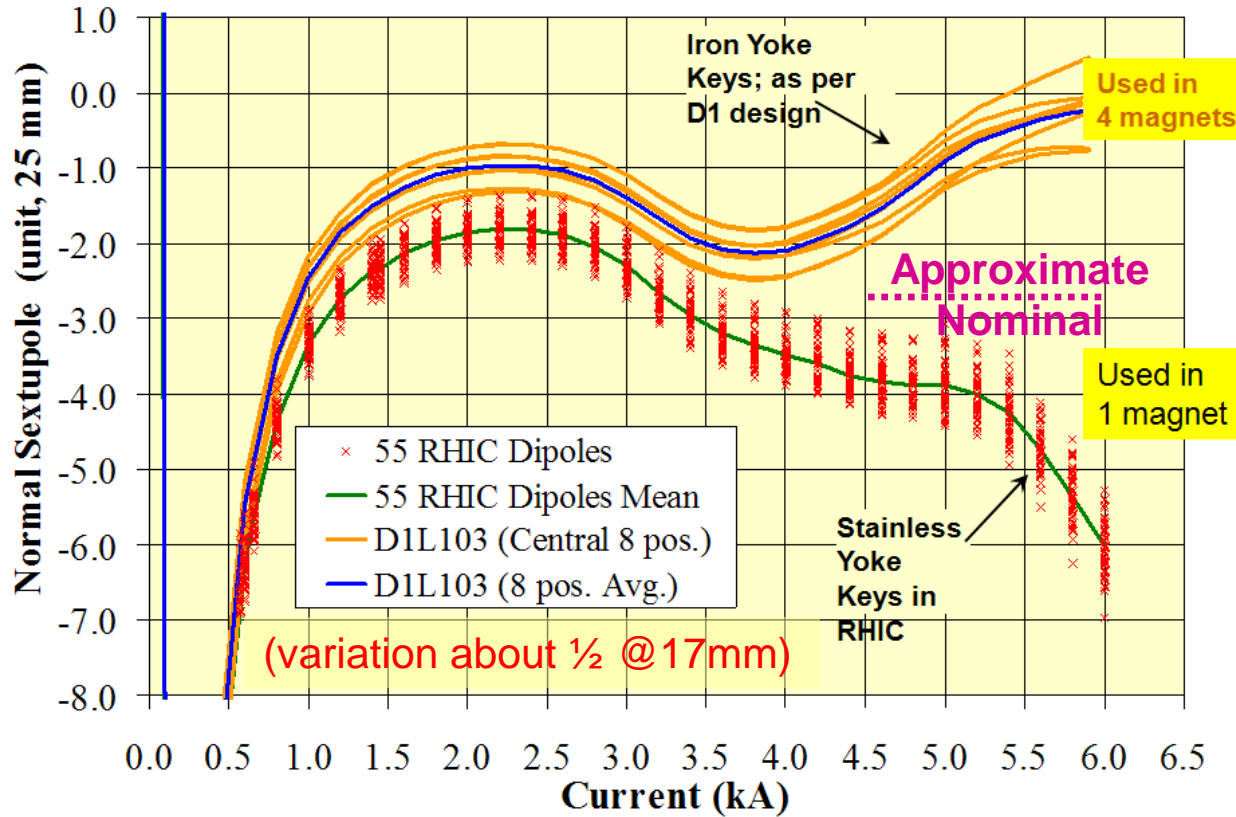
- Coldmass in cryostat gets connected to the feed-can for cold testing.
- The surface outside the stainless steel shell is open and hence some adjustments could, in principle, be made there without a major operation like cutting the weld of helium vessel, etc.
- We propose iron shims of nominal thickness attached to the shell with adjustment in the value to adjust b_3 saturation.

In the first magnet, the coldmass will anyway be taken out of the cryostat after the cold measurements before it is shipped to CERN. In the second coldmass, it will be taken out for this adjustment, if needed. In a large scale operation for other applications, one can setup a method where the shim thickness can be adjusted without taking coldmass out.

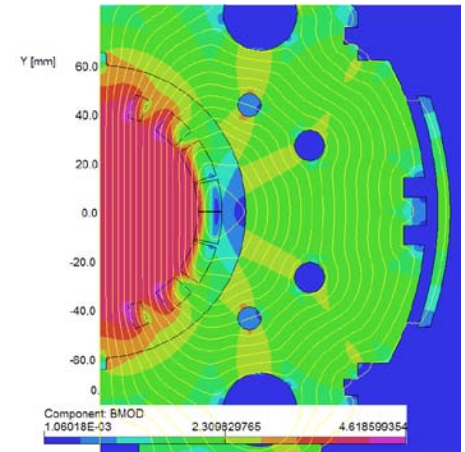


Correction of Saturation-induced Sextupole (in brief)

Warm-Cold Offsets in D1L103 & RHIC Dipoles



Approximate range of adjustment with attached iron shims



Note: Iron shims can be used to minimize either b_3 saturation or the value of b_3 at the design current (5.6 kA)

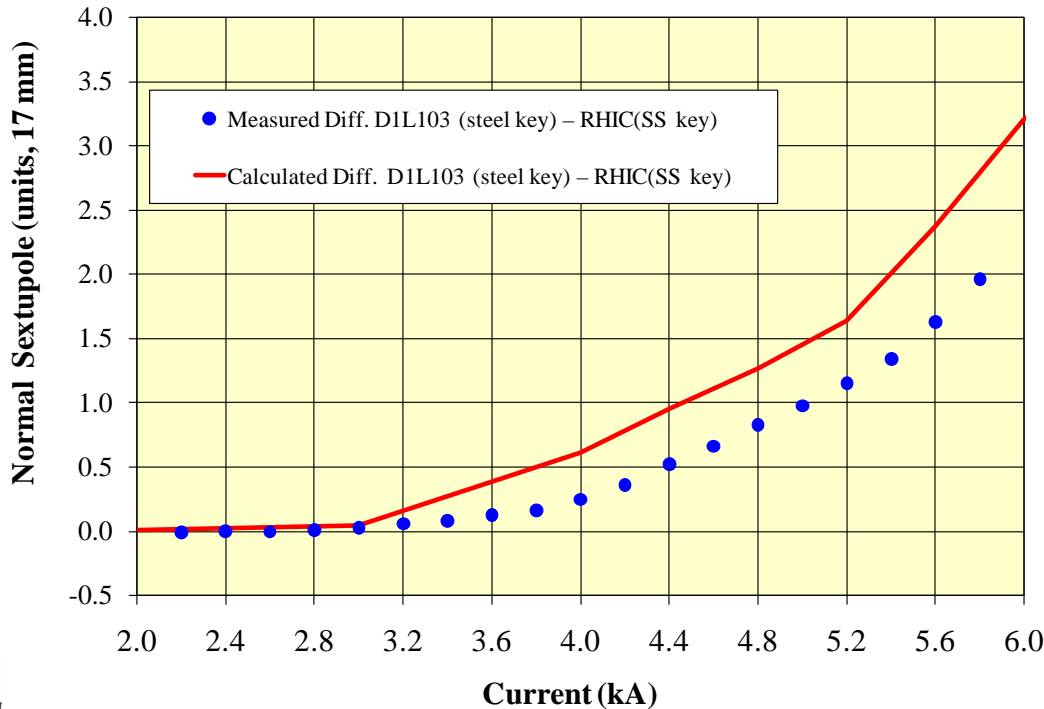


Measured and Calculated Difference in Field Harmonics between Steel Keys (low carbon steel) and SS (air) Keys

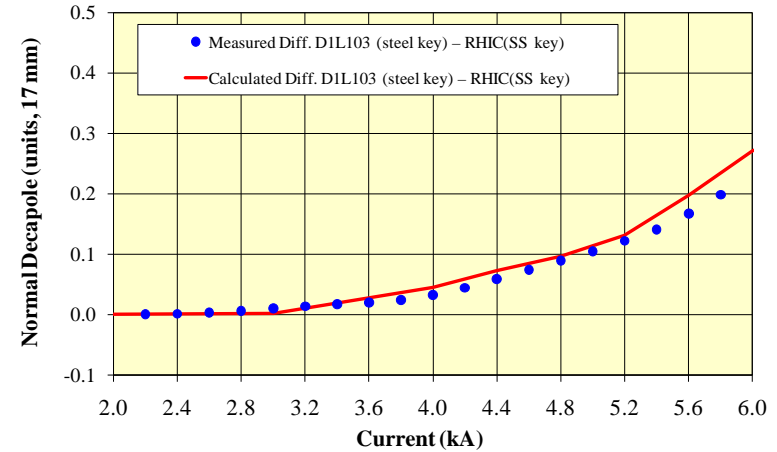
(Reference radius = 17 mm)

- Calculations assumes magnetic properties of steel key to be as good as that of yoke steel.
- This is not realistic and hence expect the change to be an over-estimate.

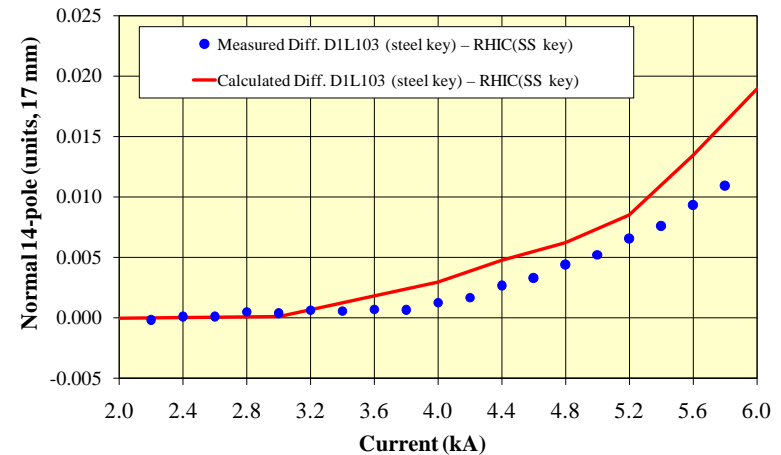
Difference in Saturation of D1 and RHIC Dipoles



Difference in Saturation of D1 and RHIC Dipoles



Difference in Saturation of D1 and RHIC Dipoles



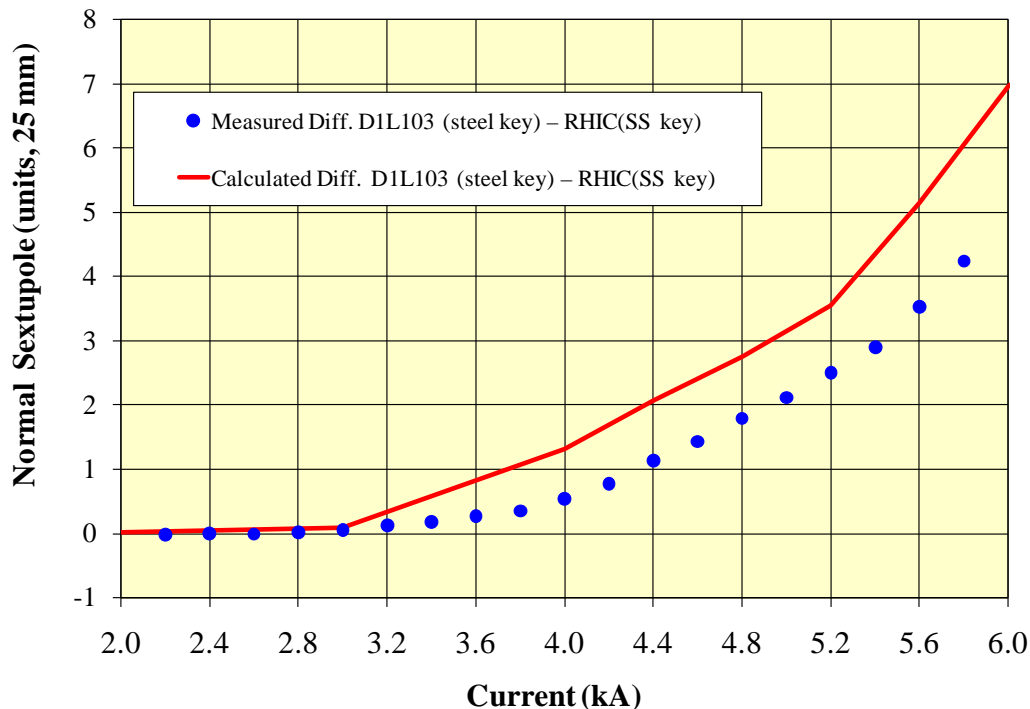


Measured and Calculated Difference in Field Harmonics between Steel Keys (low carbon steel) and SS (air) Keys

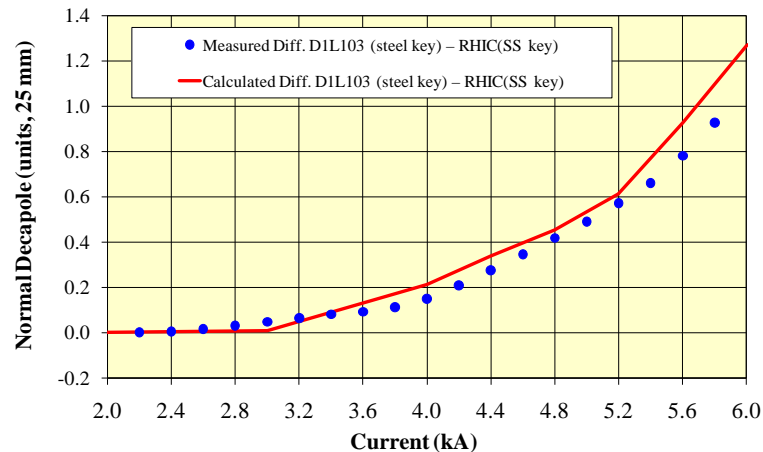
(Ref radius = 25 mm, see backup slide for 17 mm)

- Calculations assumes magnetic properties of steel key to be as good as that of yoke steel.
- This is not realistic and hence expect the change to be an over-estimate.

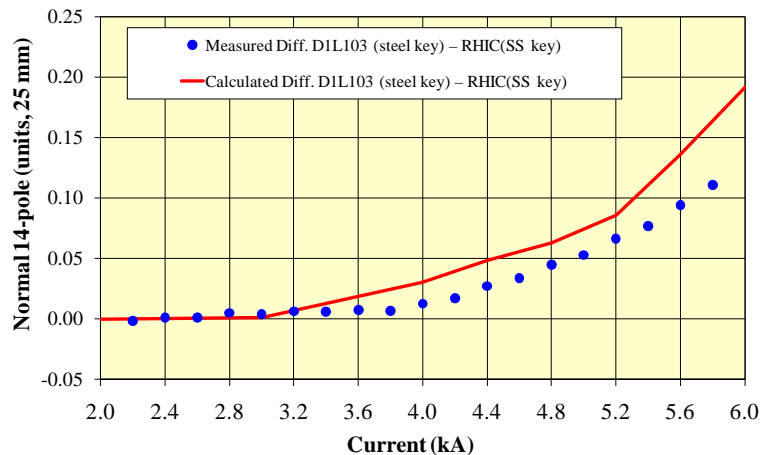
Difference in Saturation of D1 and RHIC Dipoles



Difference in Saturation of D1 and RHIC Dipoles



Difference in Saturation of D1 and RHIC Dipoles

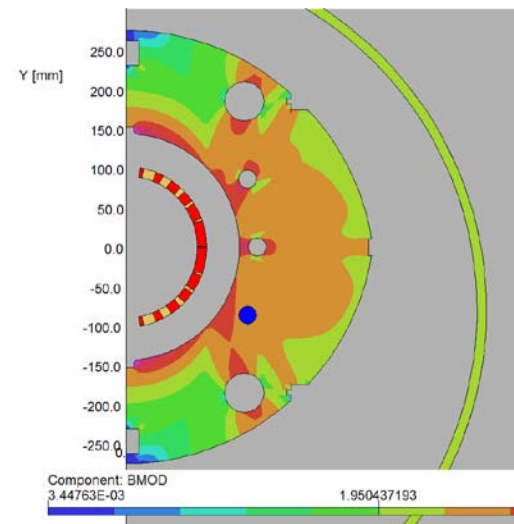
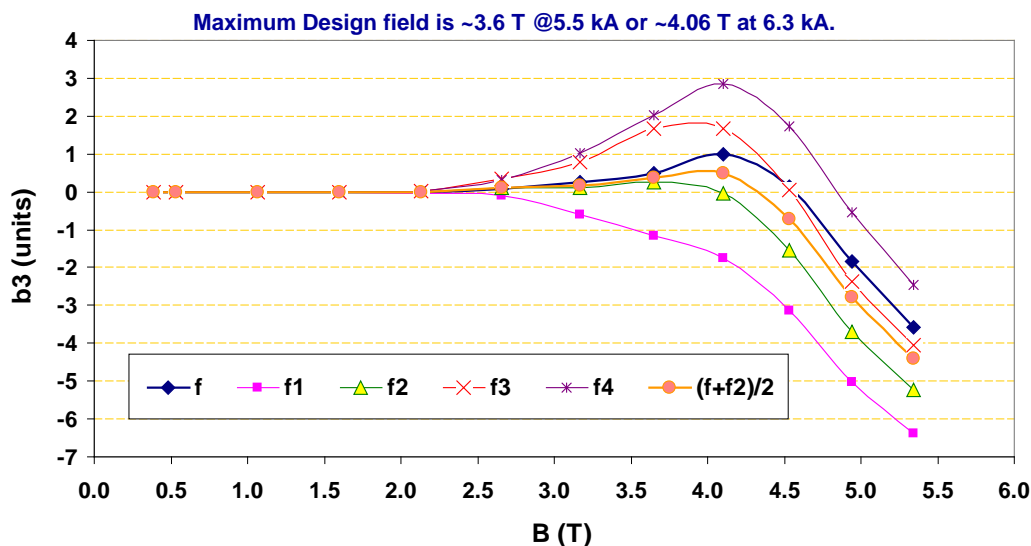




Adjustment in the Current Dependence of b_3

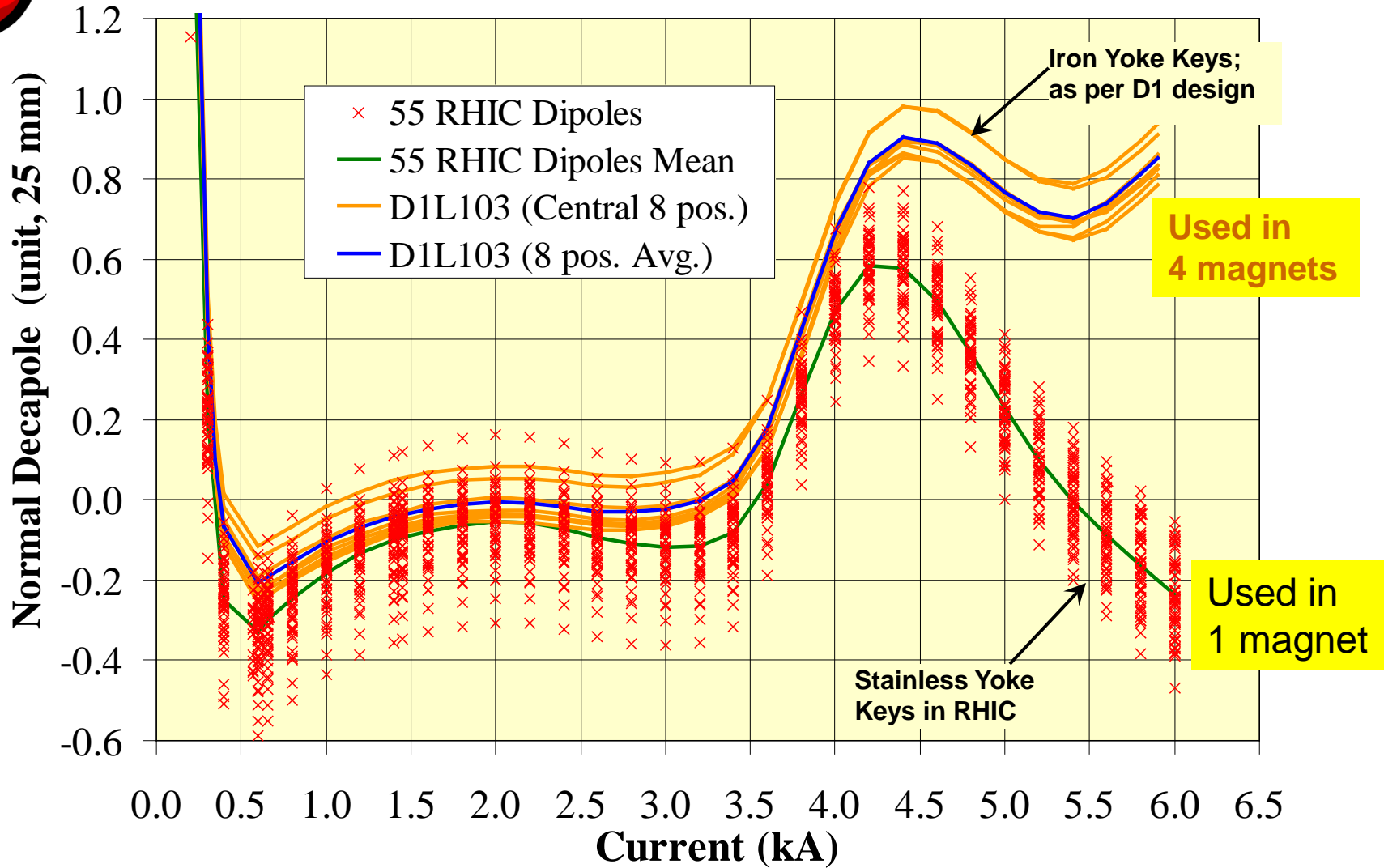
- The field dependence of sextupole (and of other saturation-induced harmonics) may be different from the expected curve due to different properties of steel.
- Additional effect may also come due to the influence of Lorentz forces on coil.
- Moreover, the warm-cold correlation also contains some uncertainty.
- All these, plus left over terms geometric harmonic adjustment, may cumulate to generate sextupole harmonic becoming larger than the specification of 2 unit.
- Earlier proposals for adjustment in saturation were based on adjusting iron rods. The proposed method achieves the same results in a more cost effective way.

Sextupole harmonic with & without various iron rods



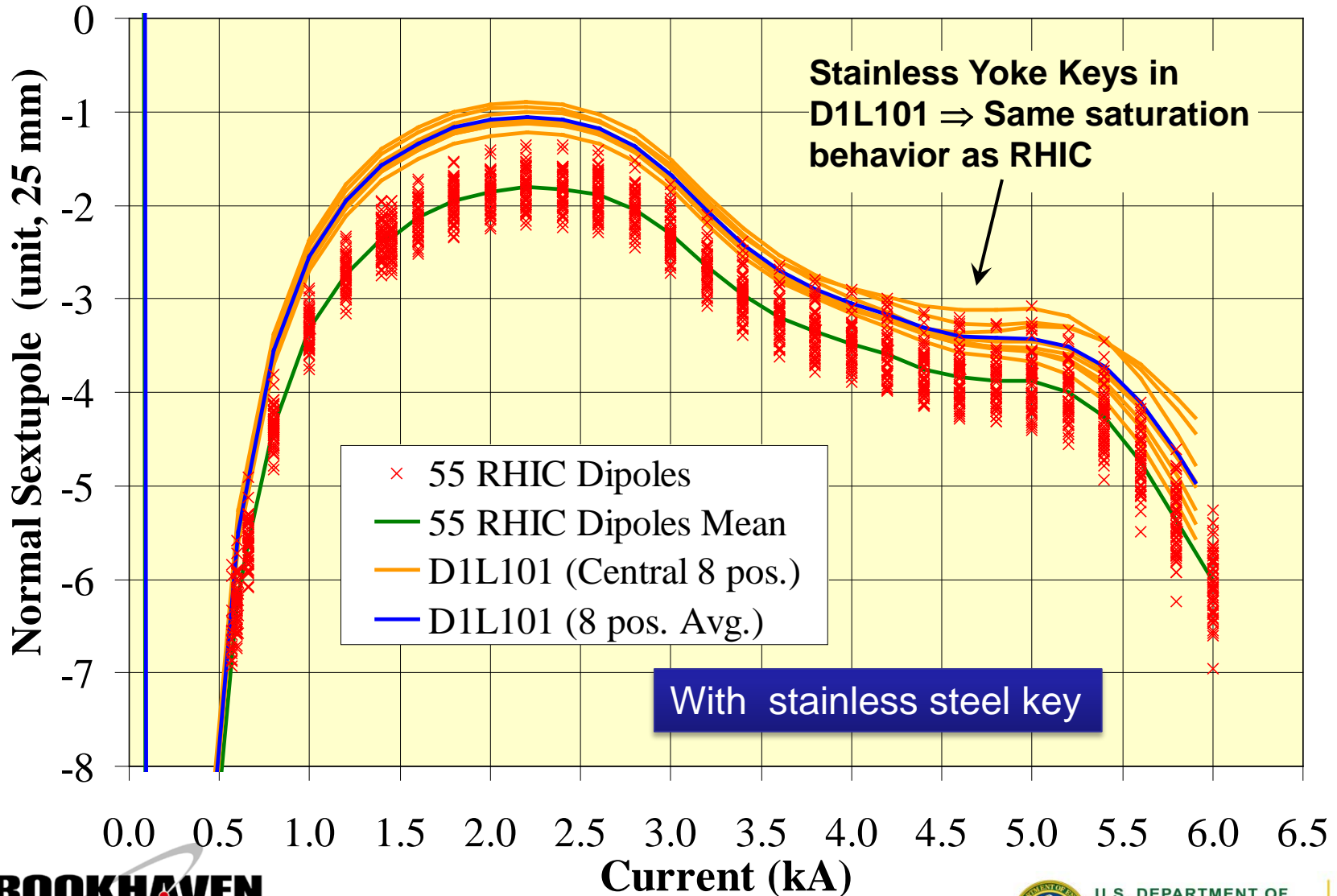


Warm-Cold Offsets in D1L103 & RHIC Dipoles





Warm-Cold Offsets in D1L101 & RHIC Dipoles

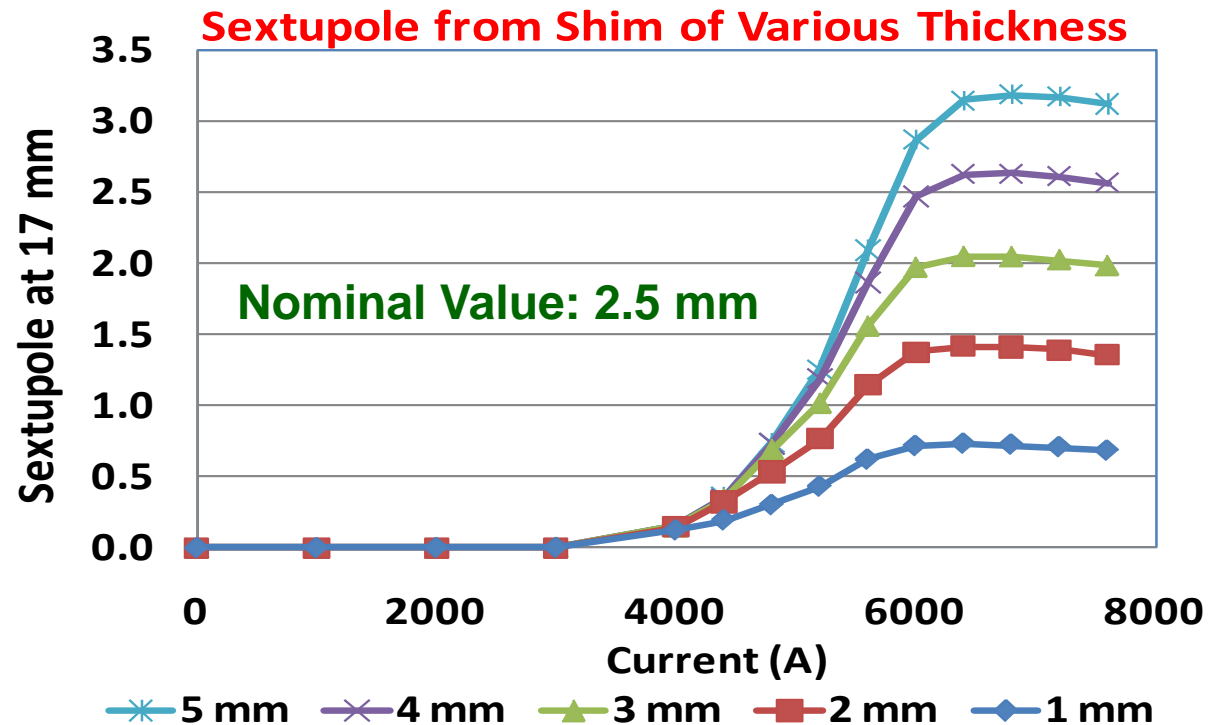




Saturation Control with Iron Shims

- Saturation induced harmonics in magnet are adjusted by adjusting the thickness of the iron shims attached to the shell.
- Max thickness ~5 mm, $\theta = \pm 20$ degree (arc ~50 mm) gives max. b_3 of ~3 (@17 mm)
- An step of 0.5 mm in shim thickness gives db_3 step of ~0.3 (APUL spec 2, all sources).

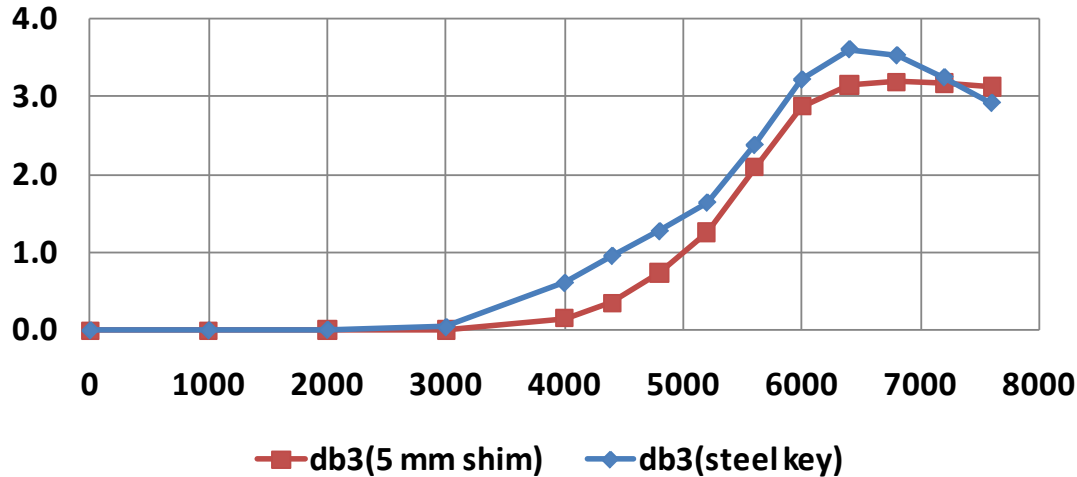
~50% of 5 mm (nominal case: 2.5 mm) gives the best b_3 solution at the design current



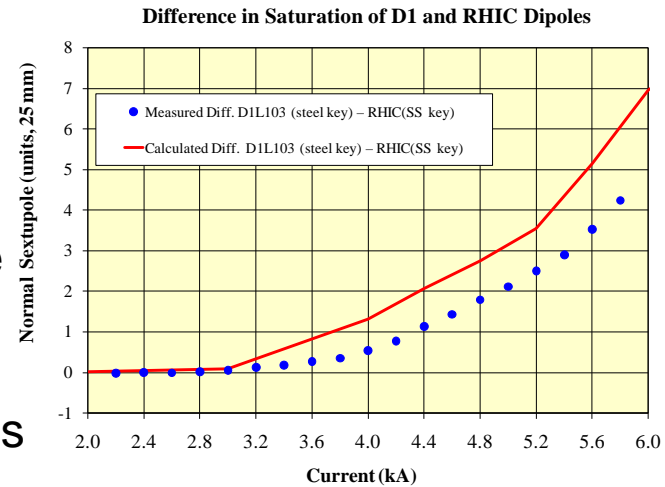
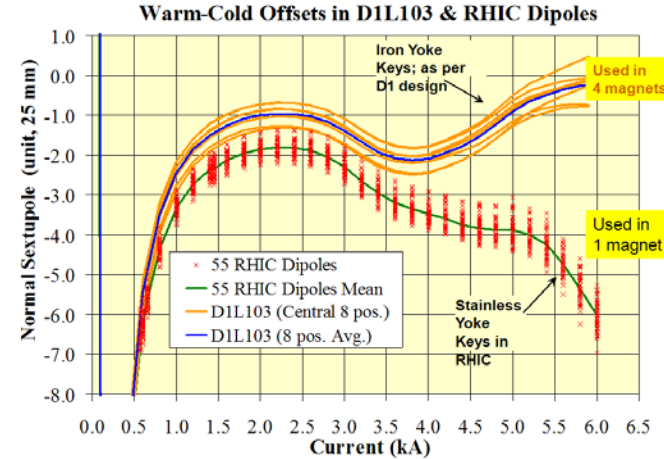


Computed Saturation from Iron Shims and Iron Keys

b₃ @17 mm as a function of current



- To first order, additional saturation induced b₃ from 50 mm steel shims behaves similar to steel keys.
- In both cases, properties of steel (BH curve, unknown) determines the actual change in b₃ saturation and hence the real measurements are useful for comparison.
- A reasonable agreement between calculations and measurements on keys gives a confidence in calculations which were supposed to produce some over correction because steel keys were assigned the yoke BH curve.



Ref radius = 25 mm