Magnetic Design

APUL D1 Dipole

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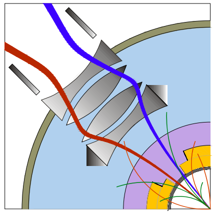
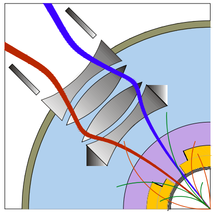
APUL CD2/3 Dry Run
13th January 2011

Outline



- Background (particularly related to field quality)
- Overall strategy in achieving the desired field quality
- Review of field quality in previous 80 mm aperture dipoles
- Strategy to assure good field quality in the APUL D1 dipoles
- Expected quench performance (computed short sample)
- Summary

Background



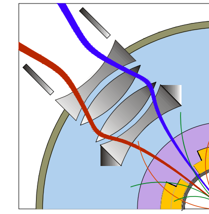
- In terms of field quality in APUL D1 dipoles, we should be ready to roll as the design is essentially the same as used in magnets that were delivered to CERN earlier. Moreover, except for a few minor differences, D1 dipoles are similar to RHIC dipoles.

- However, the present specification in the sextupole harmonic of <2 units @17 mm (or <4 units at 25 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) that were delivered earlier to CERN.

- To resolve above issue, a flexible design philosophy is being adapted to allow minor adjustments, if necessary, to ensure that both new magnets meet the specifications.

- Such approaches have been previously applied successfully in a number of magnets during the RHIC magnet production. It should work again.

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



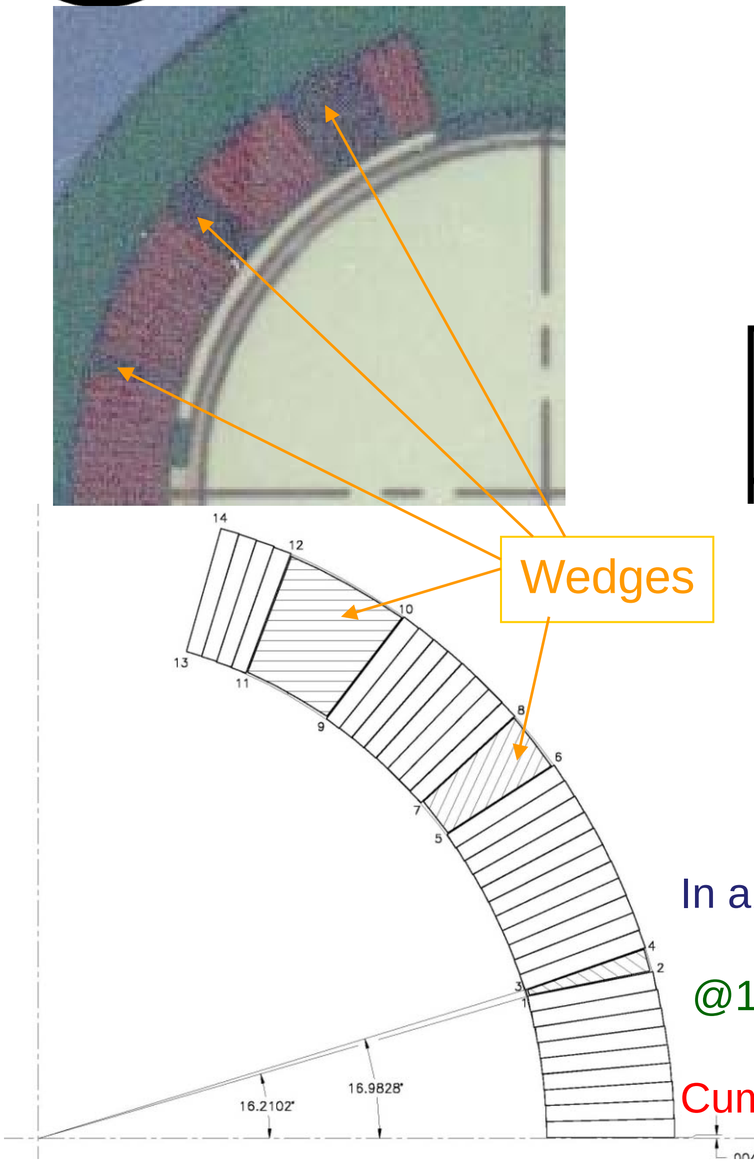


Table 4.3.2: The computed change in the transfer function and field harmonics produced by a $+25\mu m$ $(0.001'')$ change in the wedge thickness, pole width or midplane gap in the RHIC 80 mm aperture arc dipoles. The field harmonics are calculated with a 25 mm reference radius. The numbering of the wedges 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 changed	δTF $10^{-4}\frac{T}{kA}$	δb_2 10^{-4}	δb_4 10^{-4}	δb_6 10^{-4}	δb_8 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

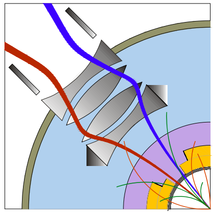
In above table b_2 is sextupole (US) - most places b_3 is used.

@17 mm reference radius, sextupole is <1/2 (~0.46) of above

Cumulative b_3 due to 25 μm errors can be > 2 units@17mm

- Plus there are other sources of errors (assembly, etc.)

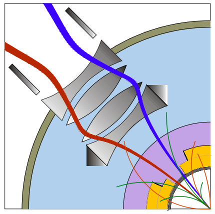
Overall Strategy for Field Quality

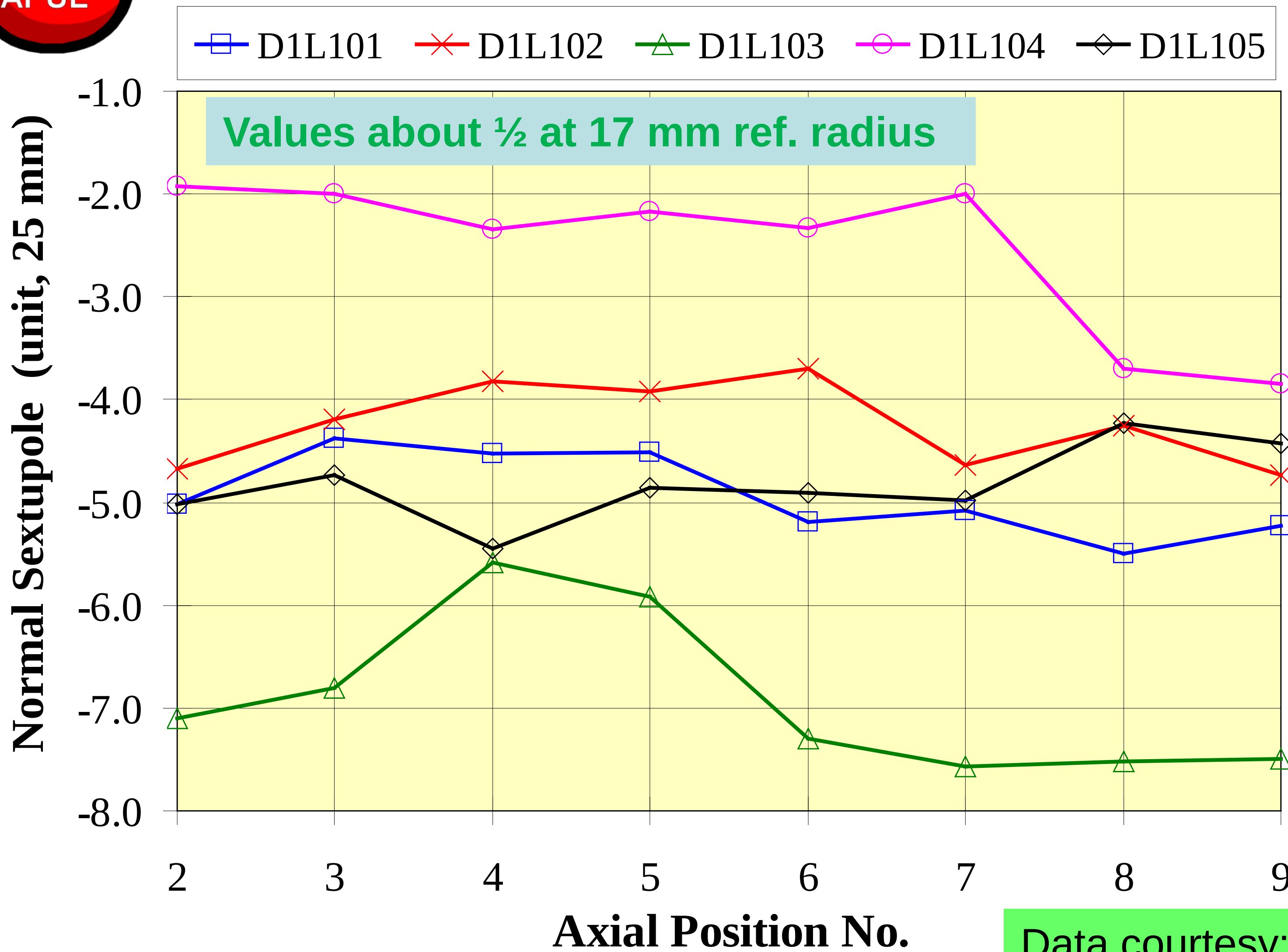


1. Measure field harmonics (warm) in the collared/yoked dipole
2. Estimate field harmonics at the design field using the warm-cold correlations based on previous production
3. Reduce geometric harmonics, if necessary, by adjusting pole shim and midplane-cap (previously developed technique)
4. Measure field quality cold after installing coldmass in cryostat
5. Adjust saturation b_3, if necessary, by using ***a new and inexpensive technique that does not require taking the magnet out of the cryostat*** (more later in the presentation)

Geometric Field Harmonics

Sextupole (b_3)
Warm Z-Scans in D1 Dipoles





The measured harmonics are the results of normal construction errors.

Two magnets did not meet the spec.

>5 unit range exceeds the in b_3 spec of ~4 units at 25 mm (~2 at 17 mm).

Data courtesy: Animesh Jain

Note: Significant variation in magnet to magnet and position to position within the same magnet

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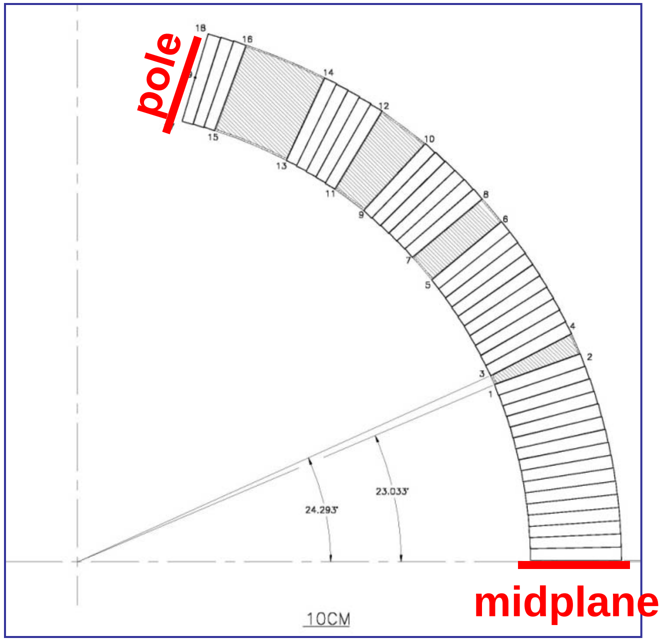
Correction in Geometric Field Harmonics

Design Philosophy:

- Start out with a flexible design that allows significant adjustability in field harmonics.
- Optimize 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 harmonics 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.
- With two parameters (adjustment in midplane and pole shim), in addition to b_3 we can also adjust b_5 or pre-stress or a combination of the two.

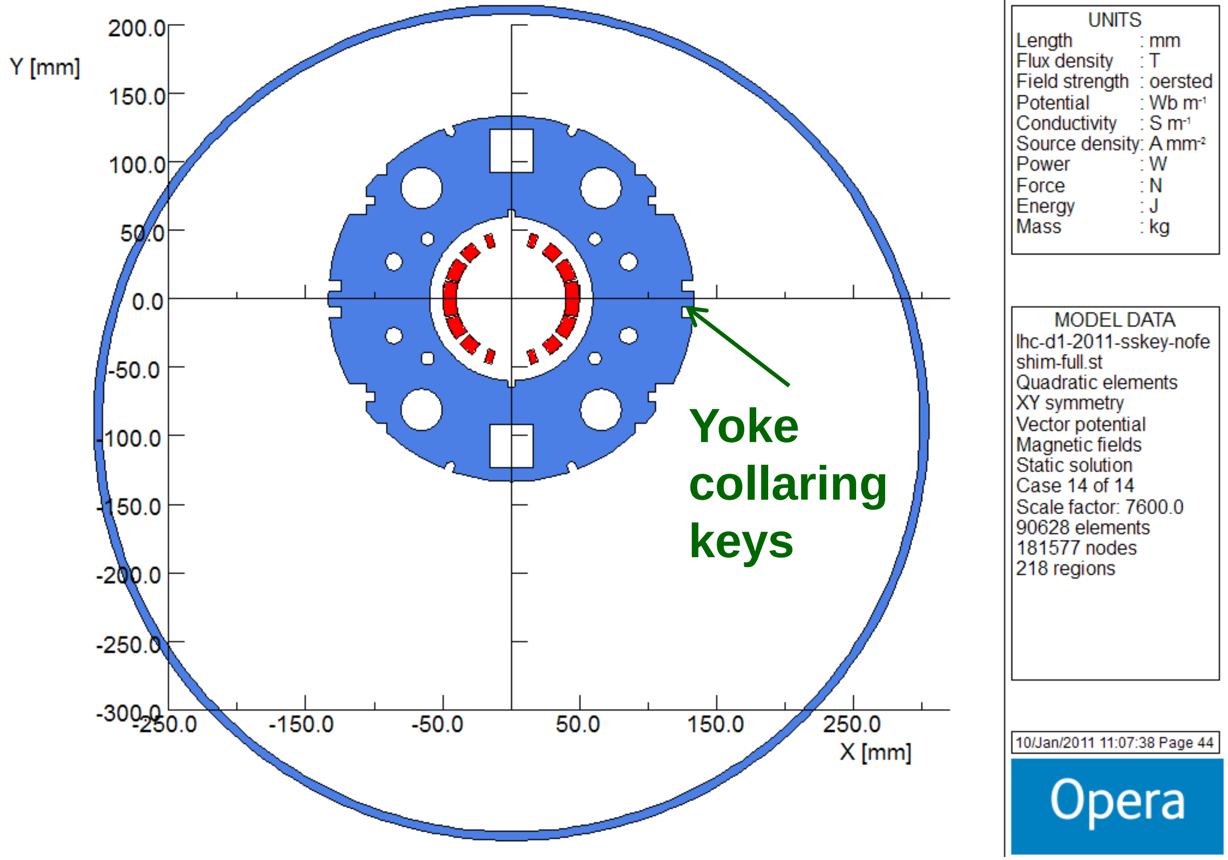


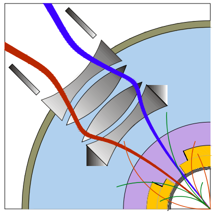
- **This approach has been successfully used in various RHIC magnets.**
- **We will use it in these APUL D1 magnets, as well.**

Field Harmonics as a Function of Field

Saturation Induced Harmonics

LHC D1 cold-mass inside the Cryostat





Note: One LHC dipole was made with stainless keys (non-magnetic) and the rest four with steel key (magnetic).

- Expect different saturation in yoke with two types of keys, particularly in a magnet where the iron at the midplane is highly saturated.

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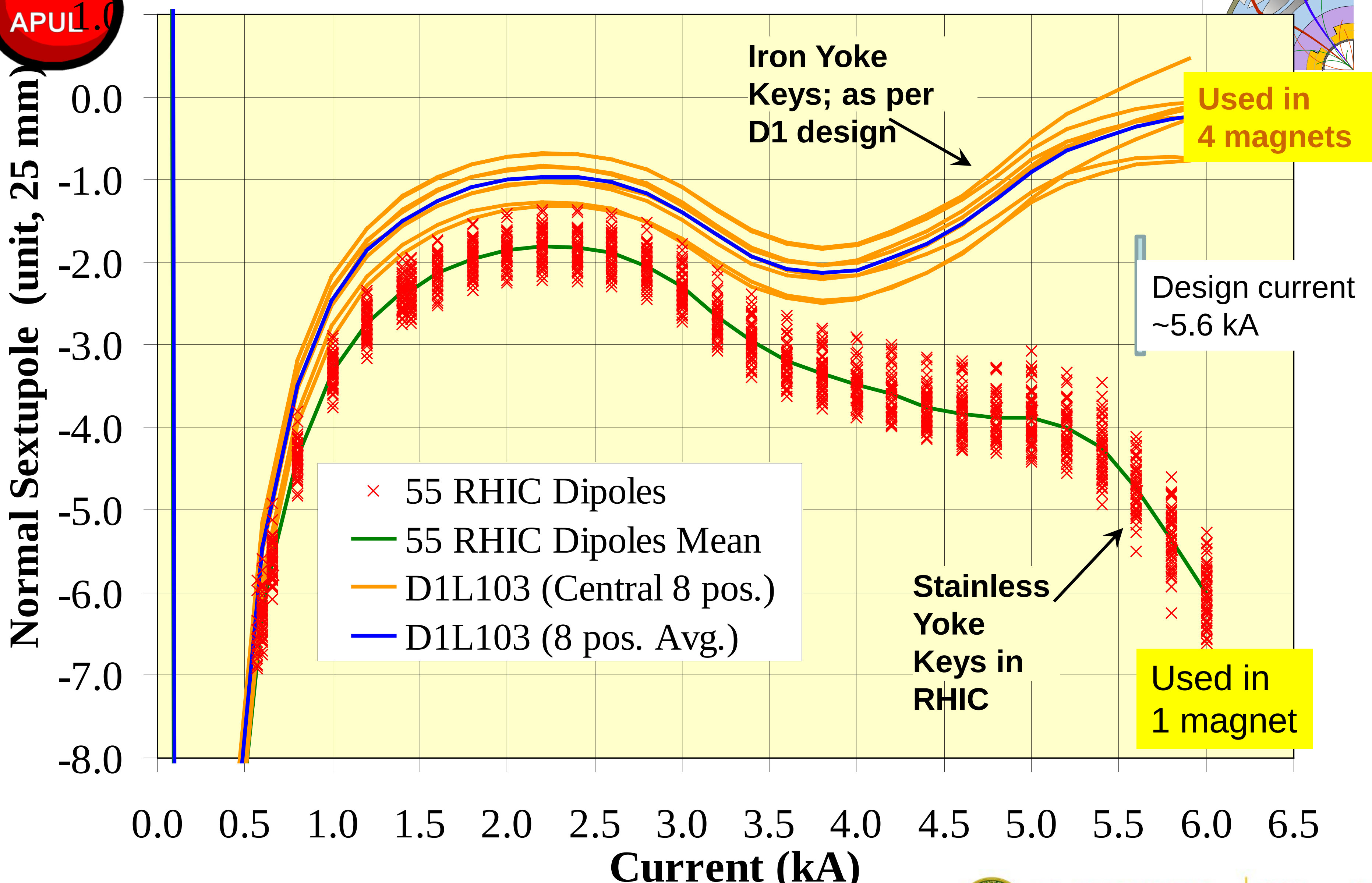
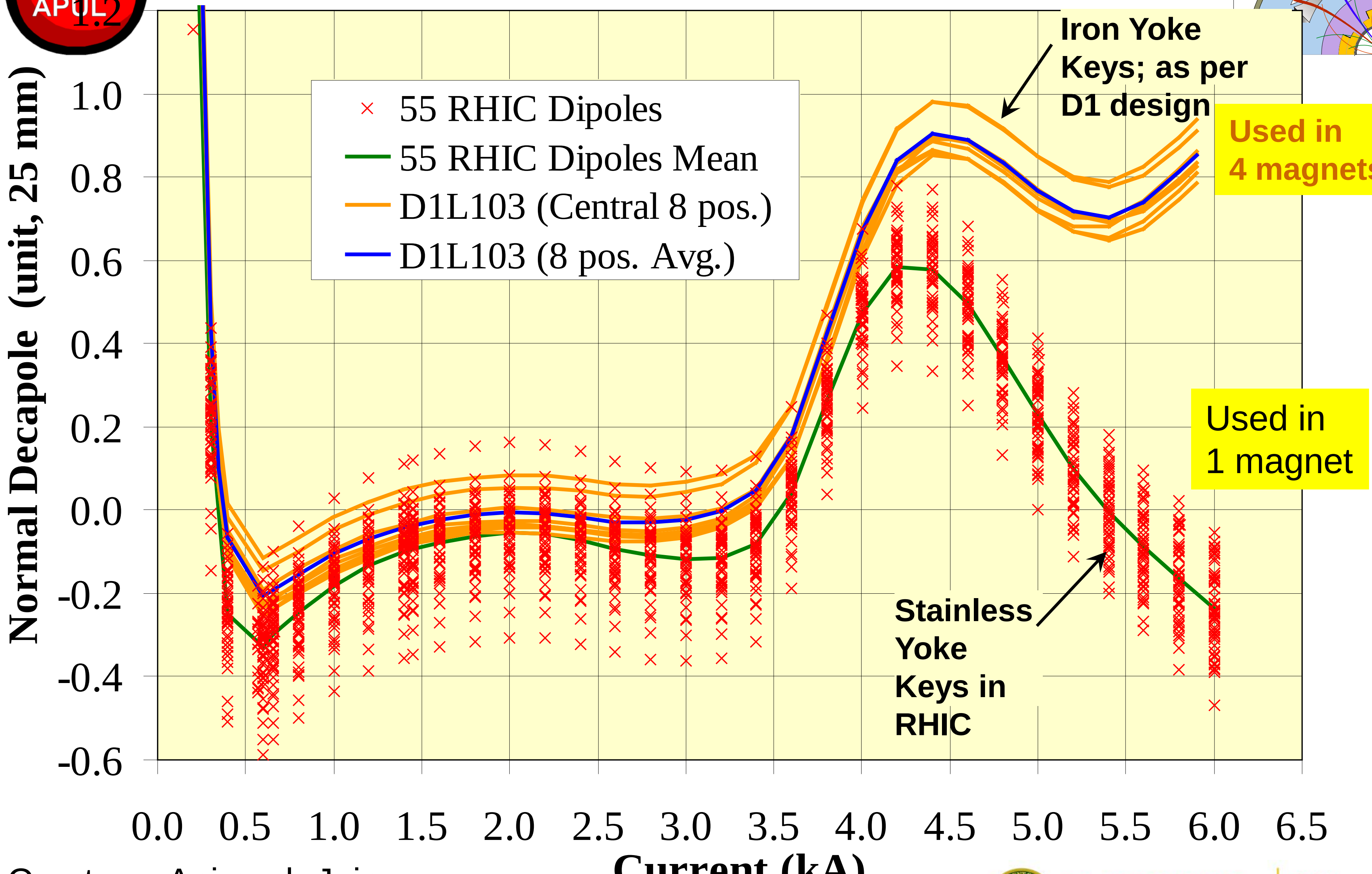
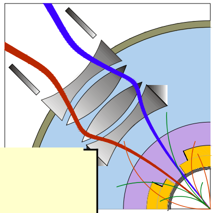
Warm-Cold Offsets in D1L103 & RHIC Dipoles



Courtesy: Animesh Jain

Warm-Cold Offsets in D1L103 & RHIC Dipoles





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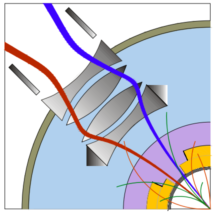
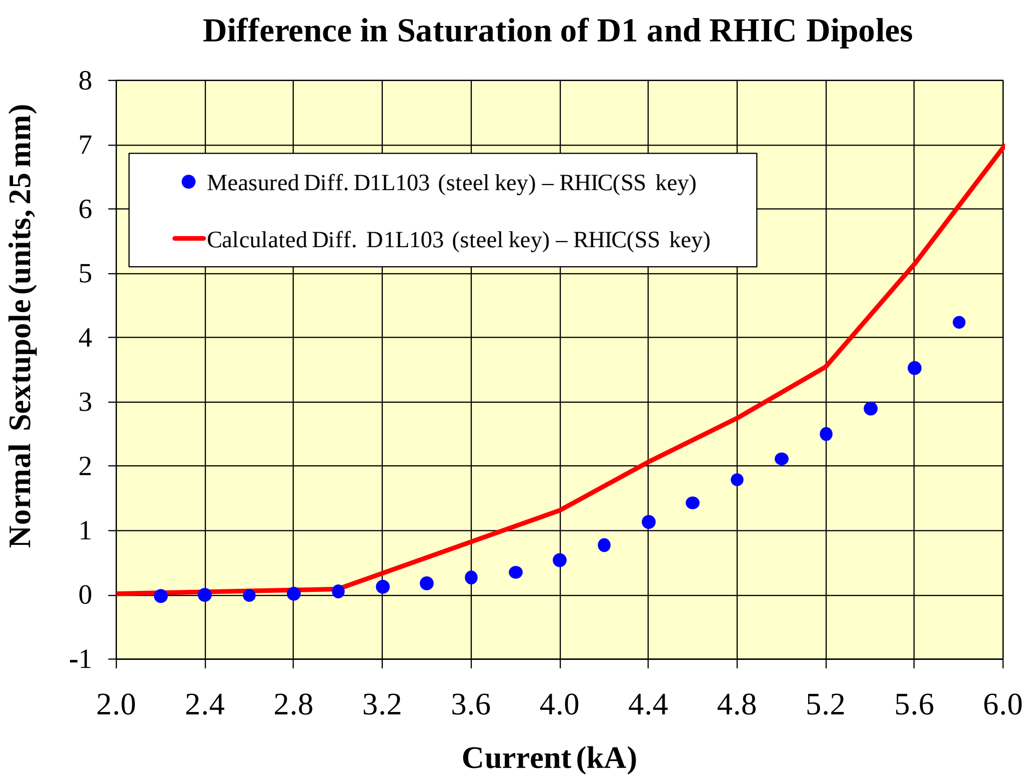


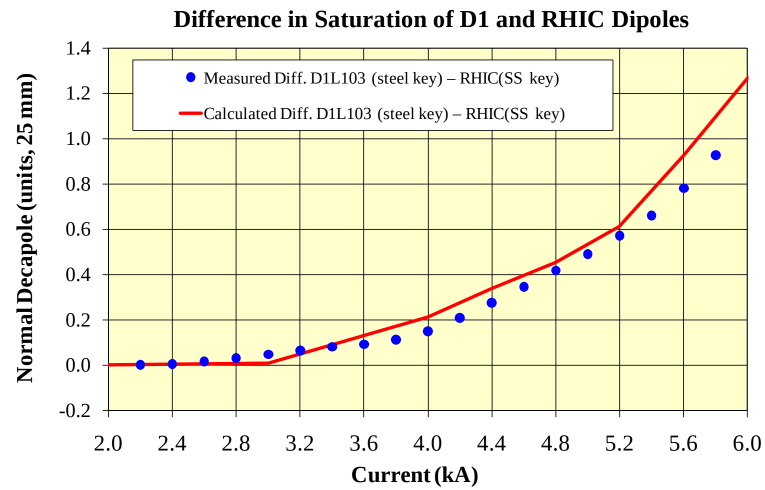
Measured and Calculated Difference in Field Harmonics between Steel Keys (low carbon steel) and SS (air) Keys

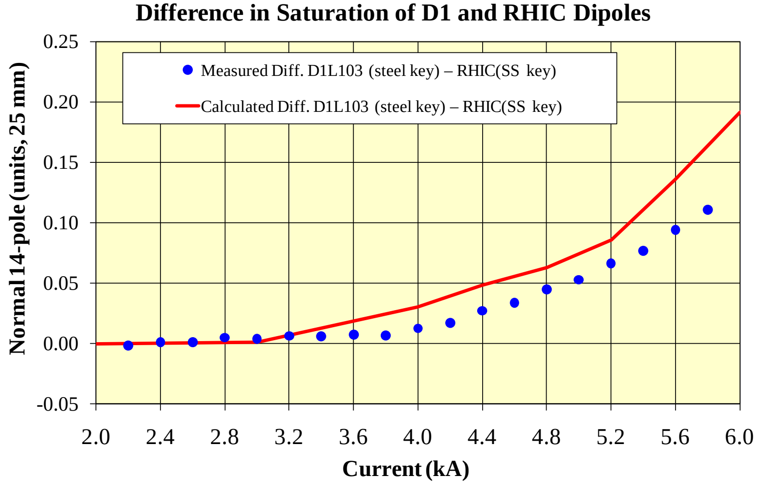
(Ref radius = 25 mm, see backup slide for 17 mm)

- 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.







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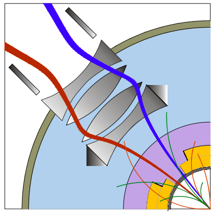
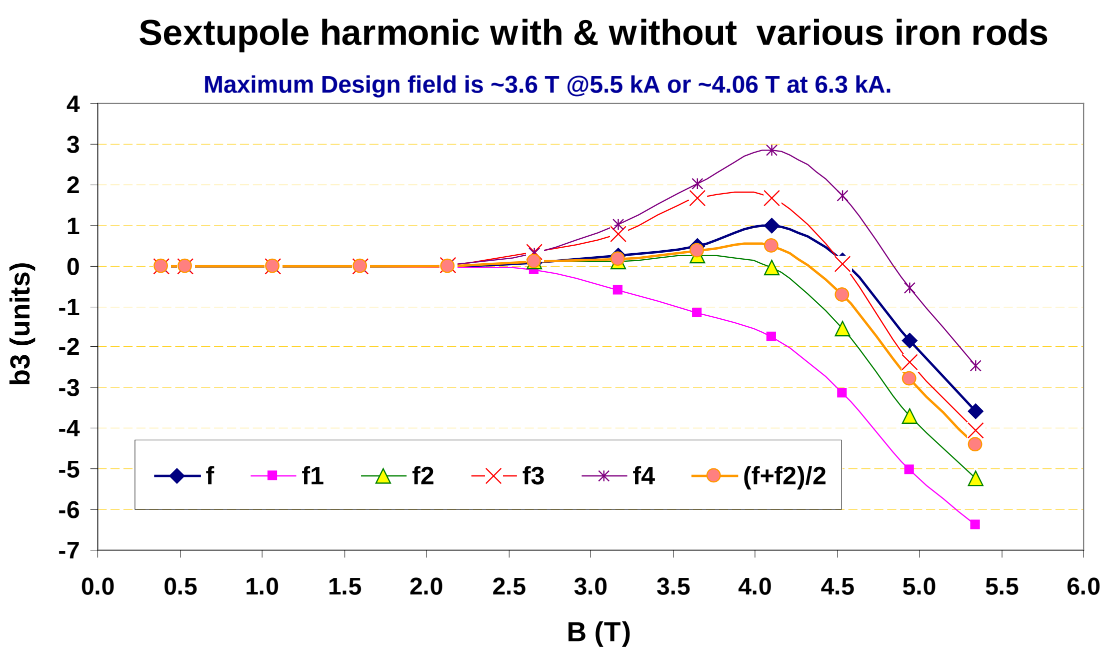
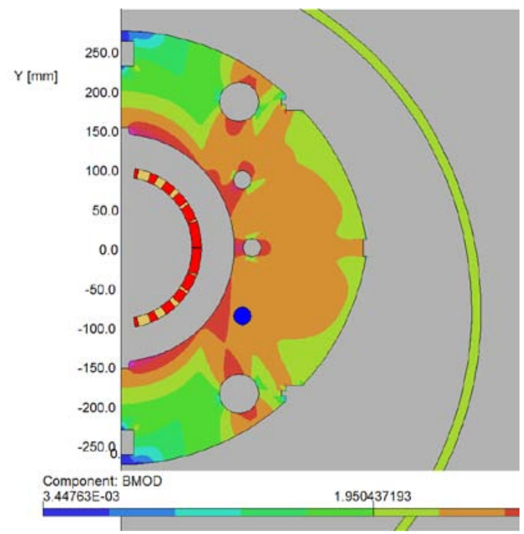
Adjustment in the Current Dependence of b_3



- 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.
- A final adjustment in saturation (for example by adjusting iron rods inside the yoke) would assure that we produce the final magnet with the required field quality.





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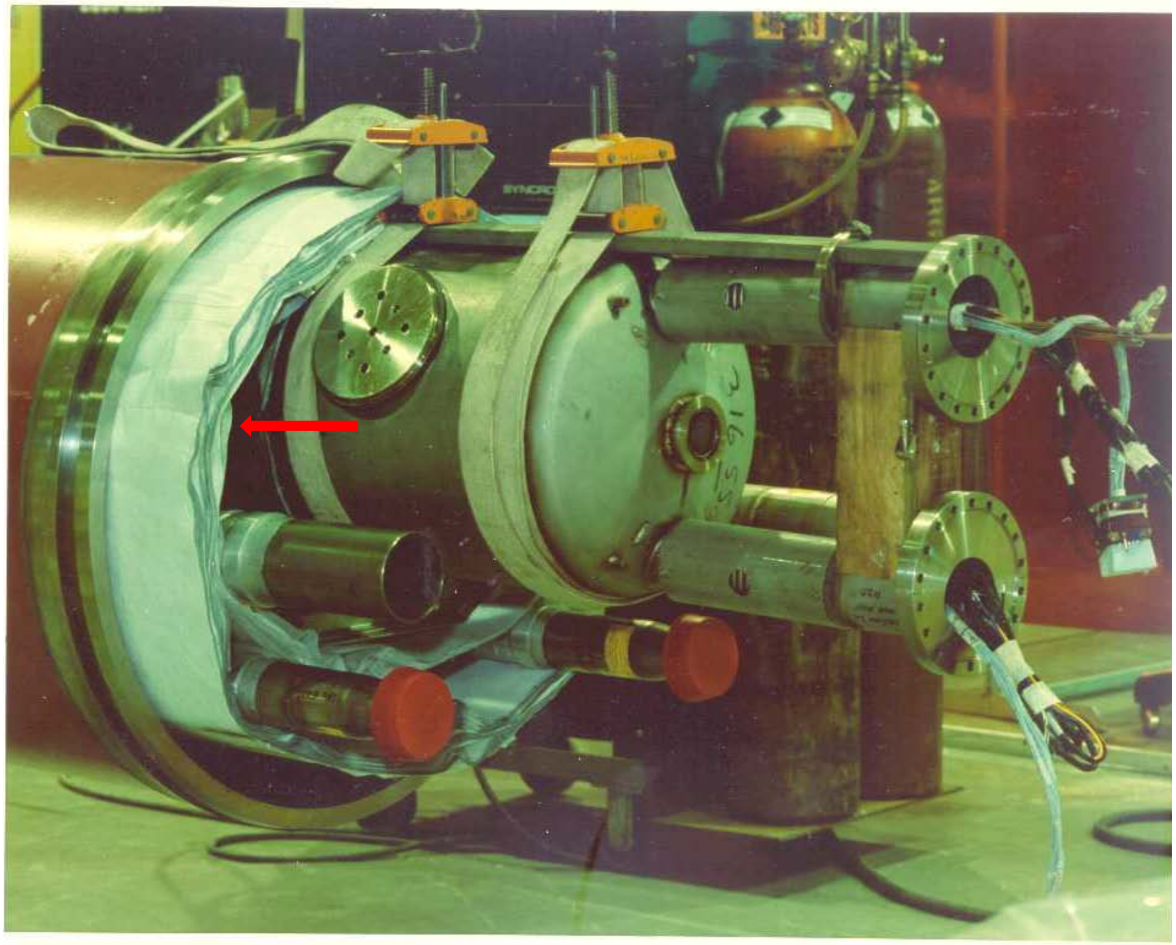
A New Method to Adjust Saturation of as-built Magnets
Installation of Saturation Control Iron Shims on SS Shell

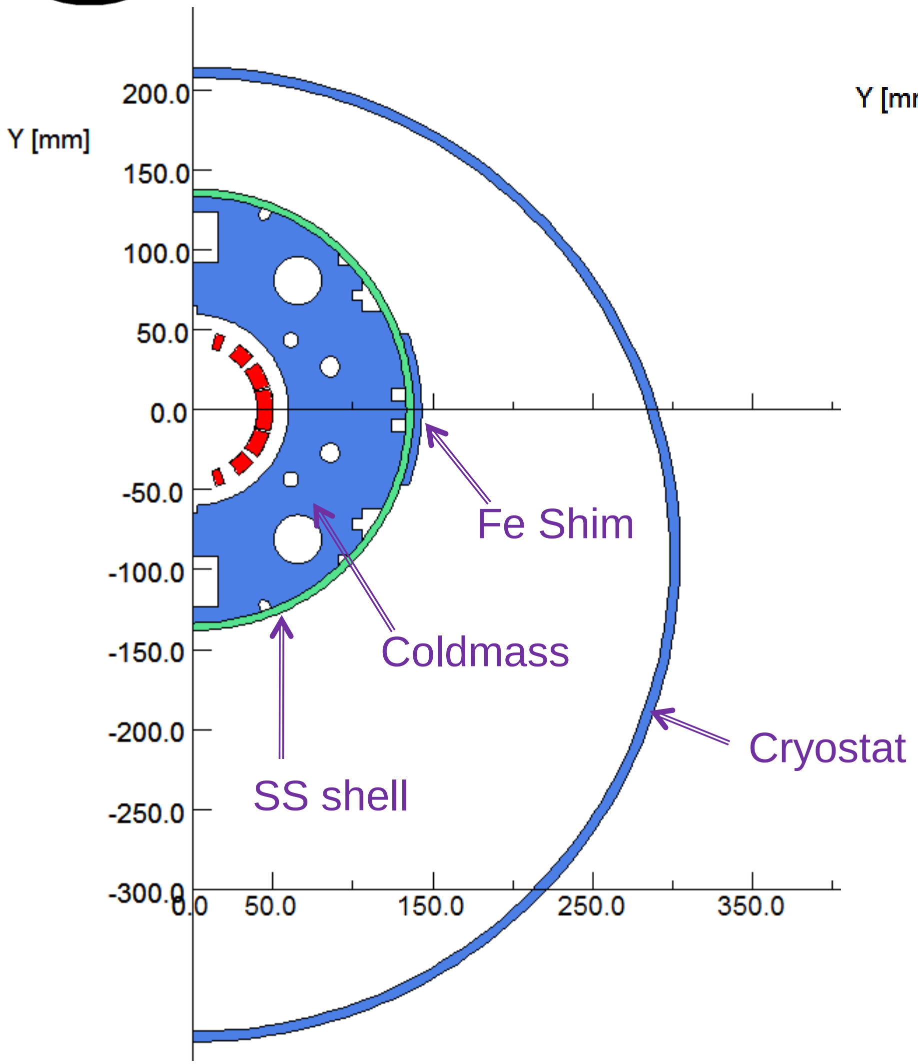


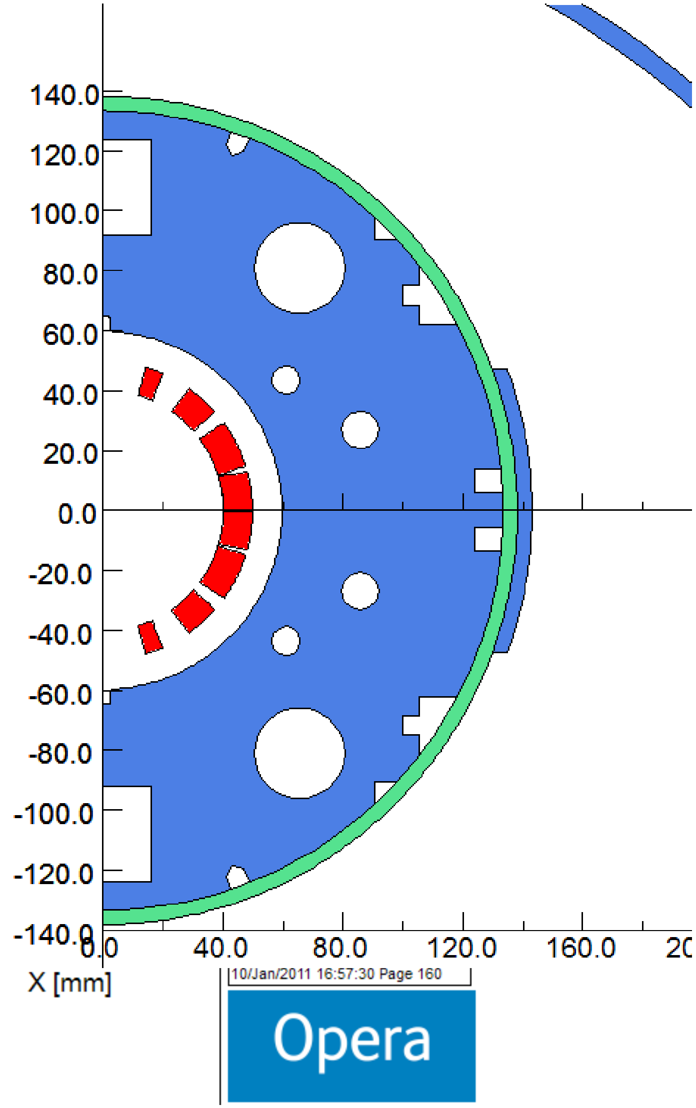
- Coldmass in cryostat gets connected to feed-can for cold testing.

- The surface outside the stainless steel shell is open and hence something can be attached to it without cutting the weld of vacuum vessel or any other major operation.

- We propose iron shims of variable thickness attached to the shell to adjust the saturation induced harmonics.

Saturation Control Iron Shims Attached to SS Shell





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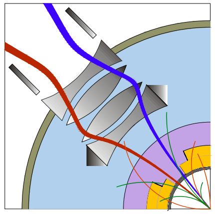
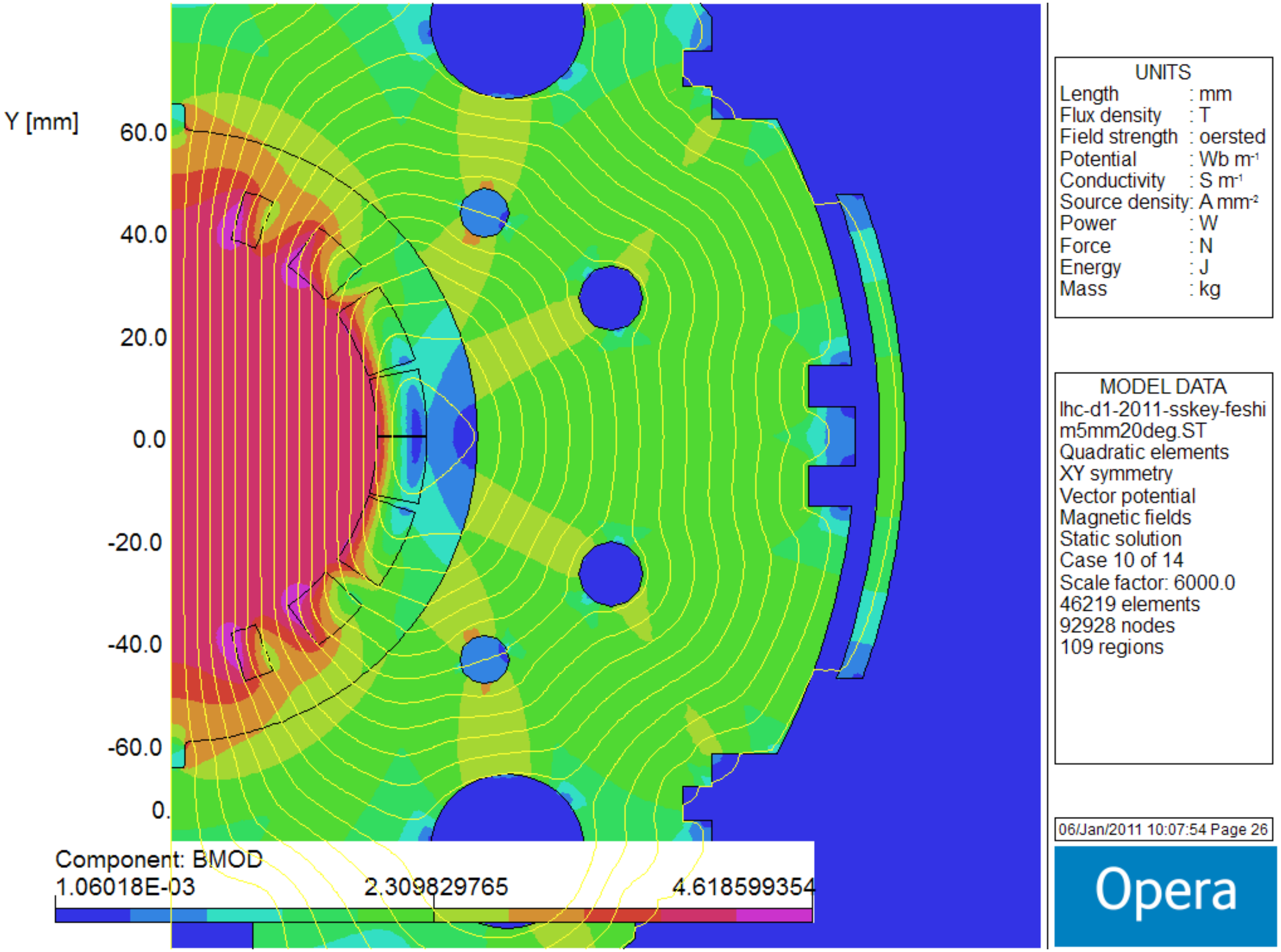
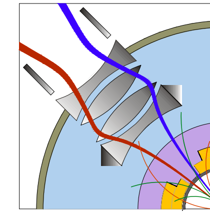
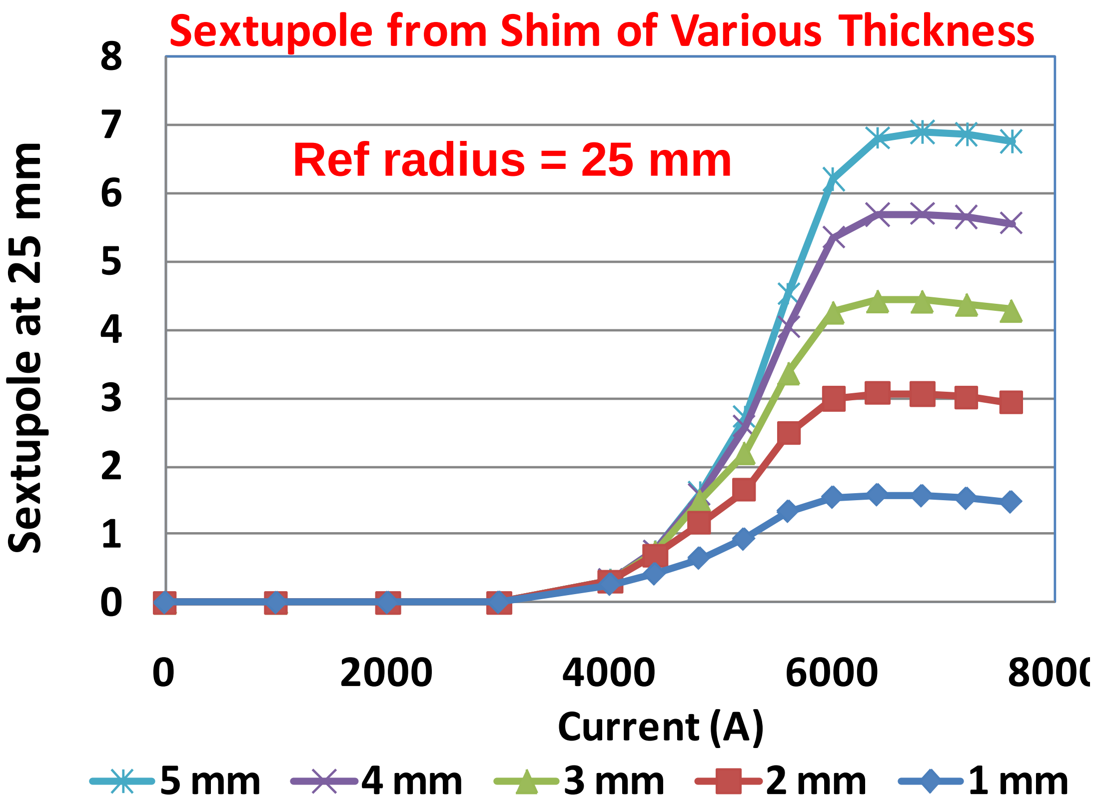


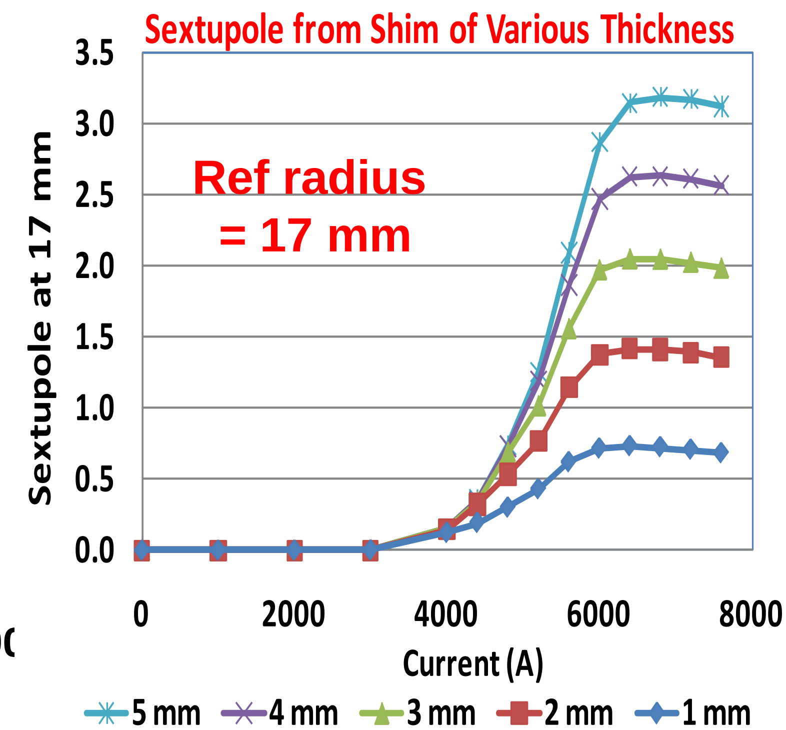


Saturation Control with Iron Shims

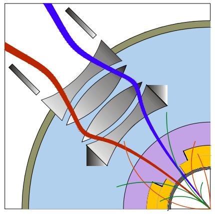


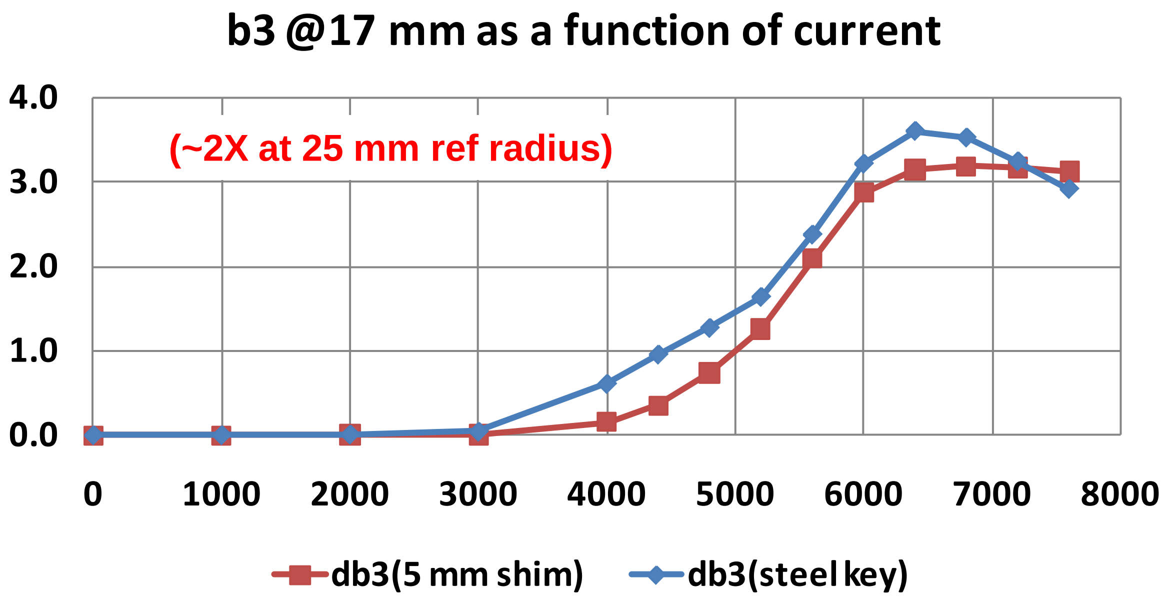
- Saturation of the iron can be adjusted by adjusting the thickness (or angular extend) of the iron shims attached to the shell.
- Max width ~5 mm, angle +/- 20 degree (arc ~50 mm) for b3=~7@25mm or ~3@17 mm
- Adjustment in thickness in 0.5 mm step for db3 =~0.7@25mm or ~0.3@17 mm.

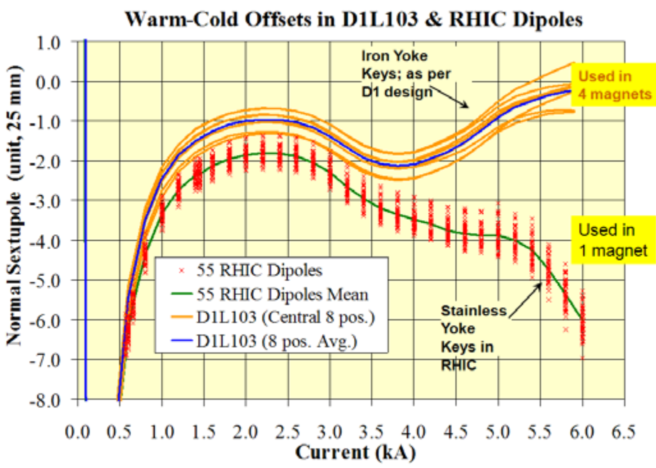


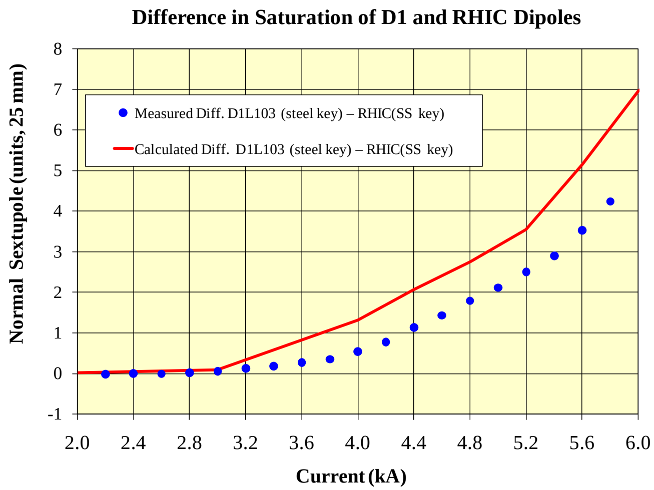


Saturation from 50mm Steel Shims or Steel Keys





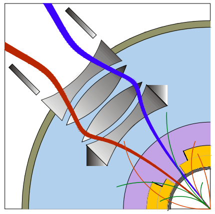




Ref radius = 25 mm

- To first order, additional saturation induced b_3 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 with steel used are important.
- ~50% of 50mm gives the least computed change in b3.
- 0% to 100% allow +/- 1.5 unit (@17 mm) adjustment.

Baseline Strategy to Adjust b3 in APUL D1 at the Design Field with Iron Shims



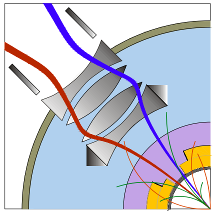
Sequence of Events:

(1) Measure first magnet cold inside the cryostat
(2) Remove from the cryostat and ship to CERN
(3) Measure second coldmass in cryostat
(4) Keep second coldmass inside the cryostat and ship to CERN with measured b3

Baseline Strategy:
(a) First cold measurement of coldmass#1 with the best guess of the shim.
(b) After the cold measurement, take coldmass outside the cryostat and adjust shims, if necessary, and send it to CERN with that shim.
(c) Second cold measurement in coldmass #2 with the above shim to confirm that the above choice was right and CERN has one magnet with right measurement.

(d) Contingency may be used to do cold measurement after (b), if desired.

Alternate Strategy to Adjust b3 in APUL D1 at the Design Field with Iron Shims



The following strategy is based on the fact that it is much easier to change the outside shell shim when the coldmass is outside the cryostat (we still should have the provision of adjusting when it is inside).

Alternate Strategy:

(a) First cold measurement of coldmass#1 with 1/3 magnet full shim, 1/3 half shim and 1/3 no shim.

(b) After the cold measurement, take coldmass out of the cryostat; determine the right shim with the help of above measurements and send it to CERN with that shim.

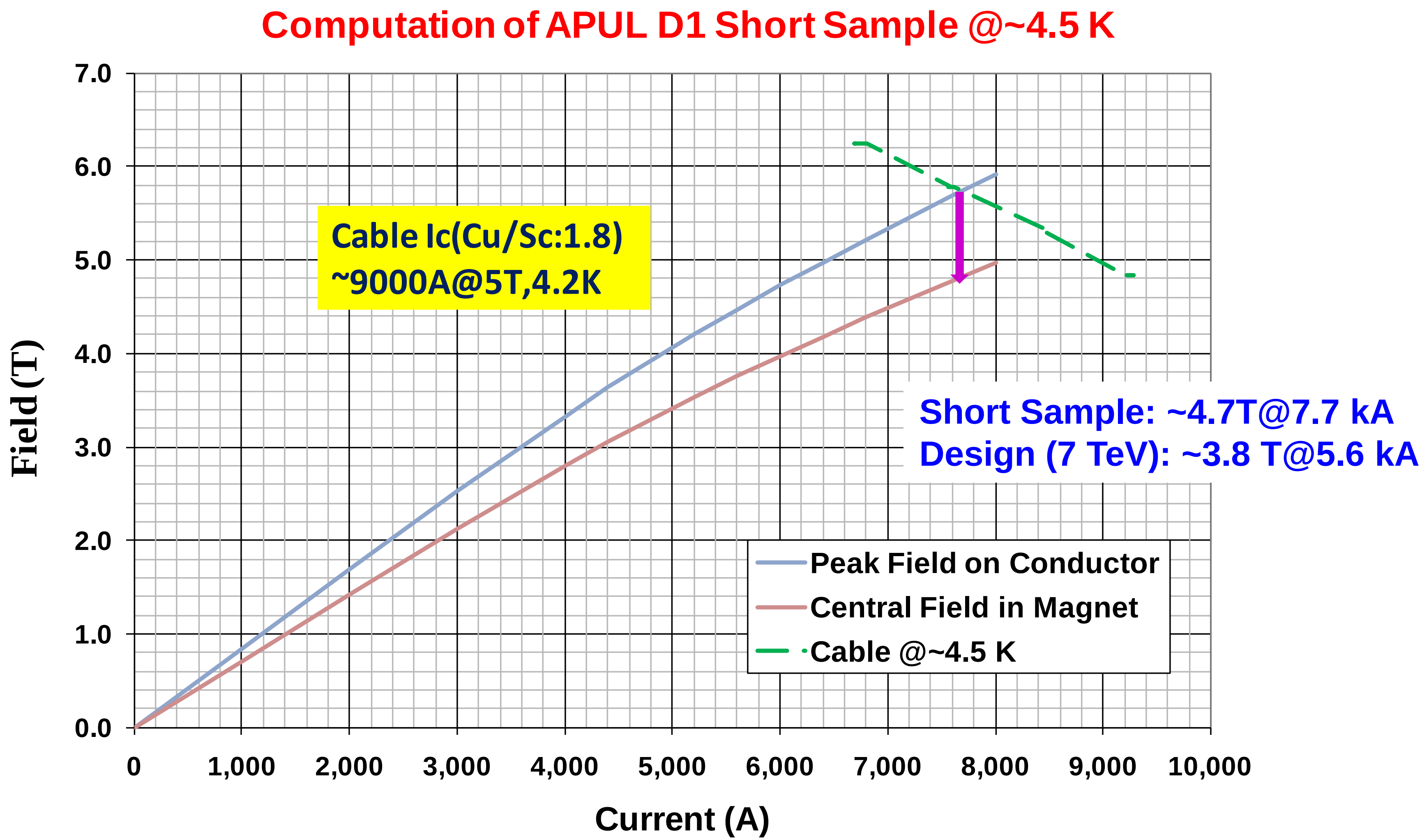
(c) Second cold measurement in coldmass #2 with the above shim to confirm that the above choice was right and CERN has one magnet with right measurement.

(d) Contingency may be used to do cold measurement after (b), if desired.

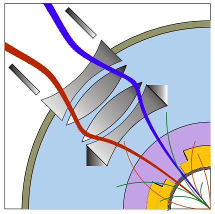
Alternate strategy is preferred as it provides the measured change in harmonics to correctly adjust the shim. It is more important as the BH curve of shim is unknown.

Computed Quench Performance (Short Sample)

Cu/Sc of ~1.8 rather than ~2.2 gives higher short sample current, however, at expense of higher current density in copper at quench



Summary

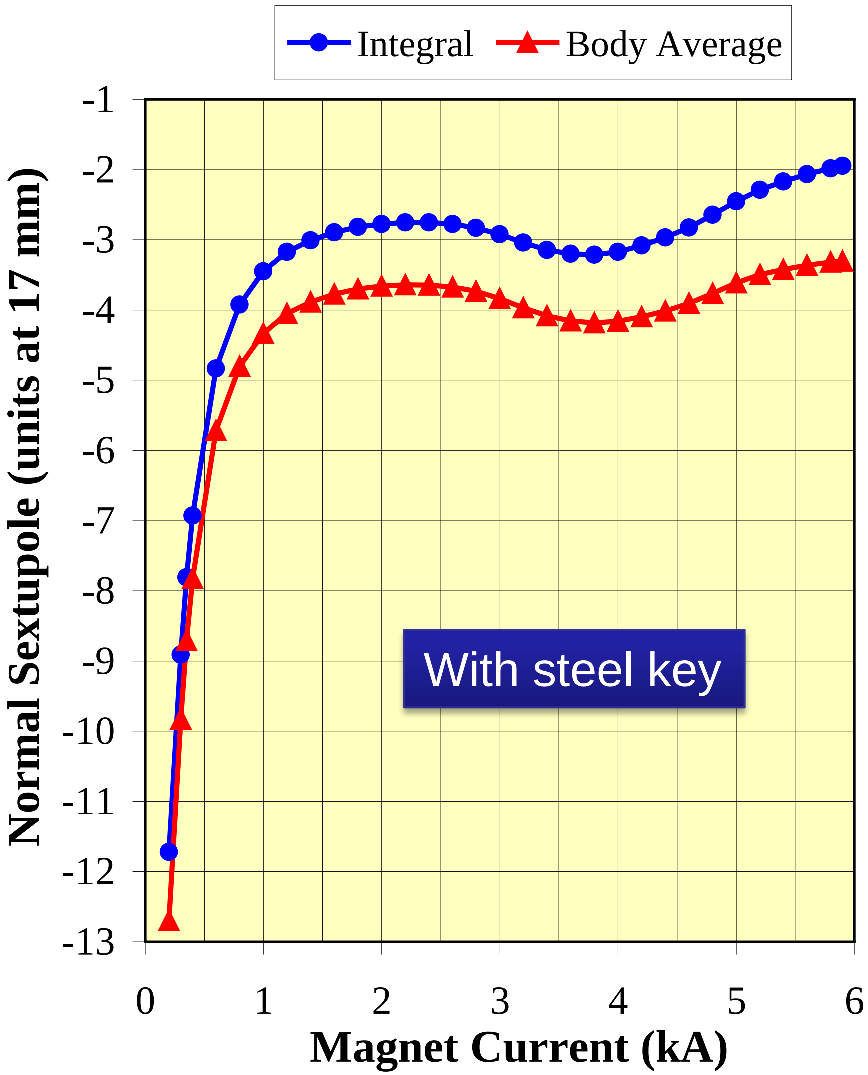


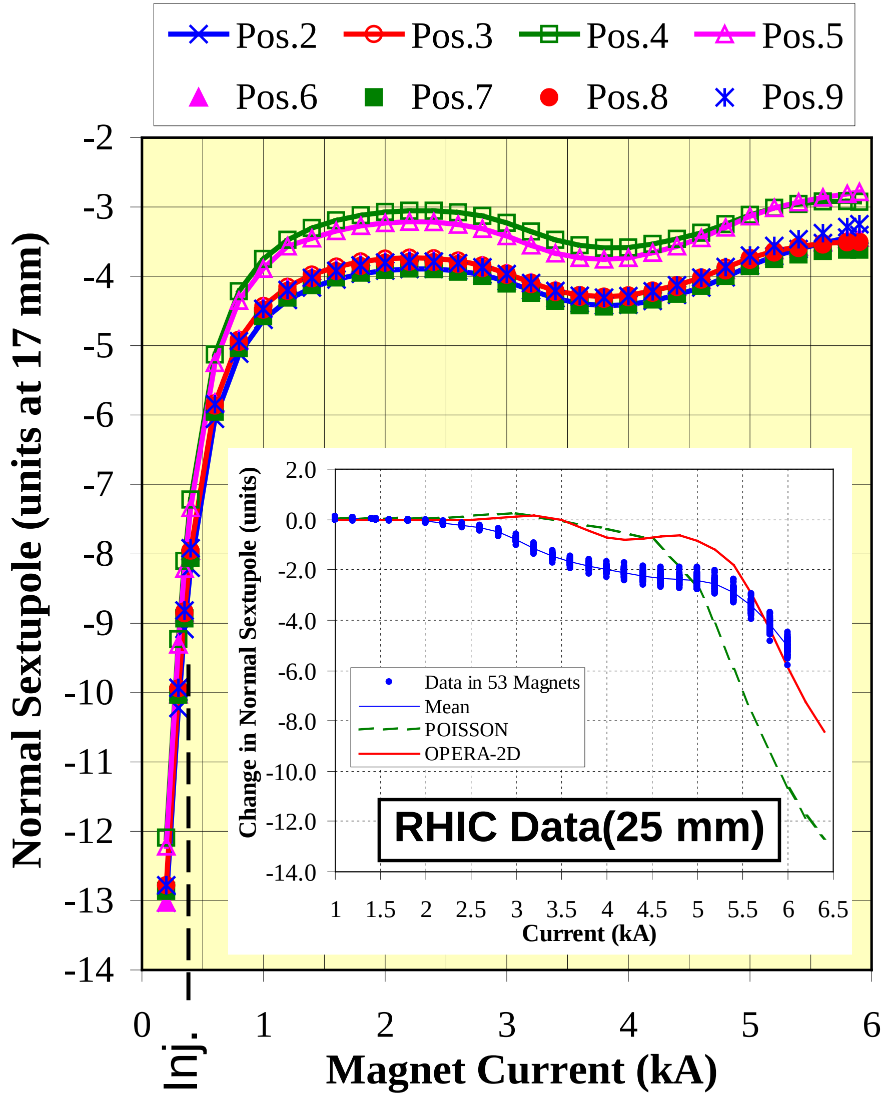
- With the flexible design, we will be able to meet the APUL D1 field quality specifications. In particular, strategies have been developed to meet tighter specification of b_3.
- We are adopting a ***value engineering*** approach to save on cost and schedule by eliminating customary magnet iterations.
- First adjustment will be carried out after warm measurements by adjusting midplane and pole shims, if needed.
- Final adjustment will be carried out after cold measurements by adjusting the iron shims on the shell, if needed.
- This new technique allows simple adjustment with coldmass inside the cryostat and thus saves on cost and time.

Back-up slides

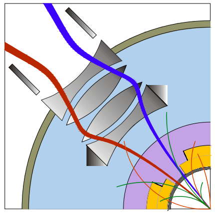
Excitation Curves (D1L103)

Integral, Body and 1 meter Interval

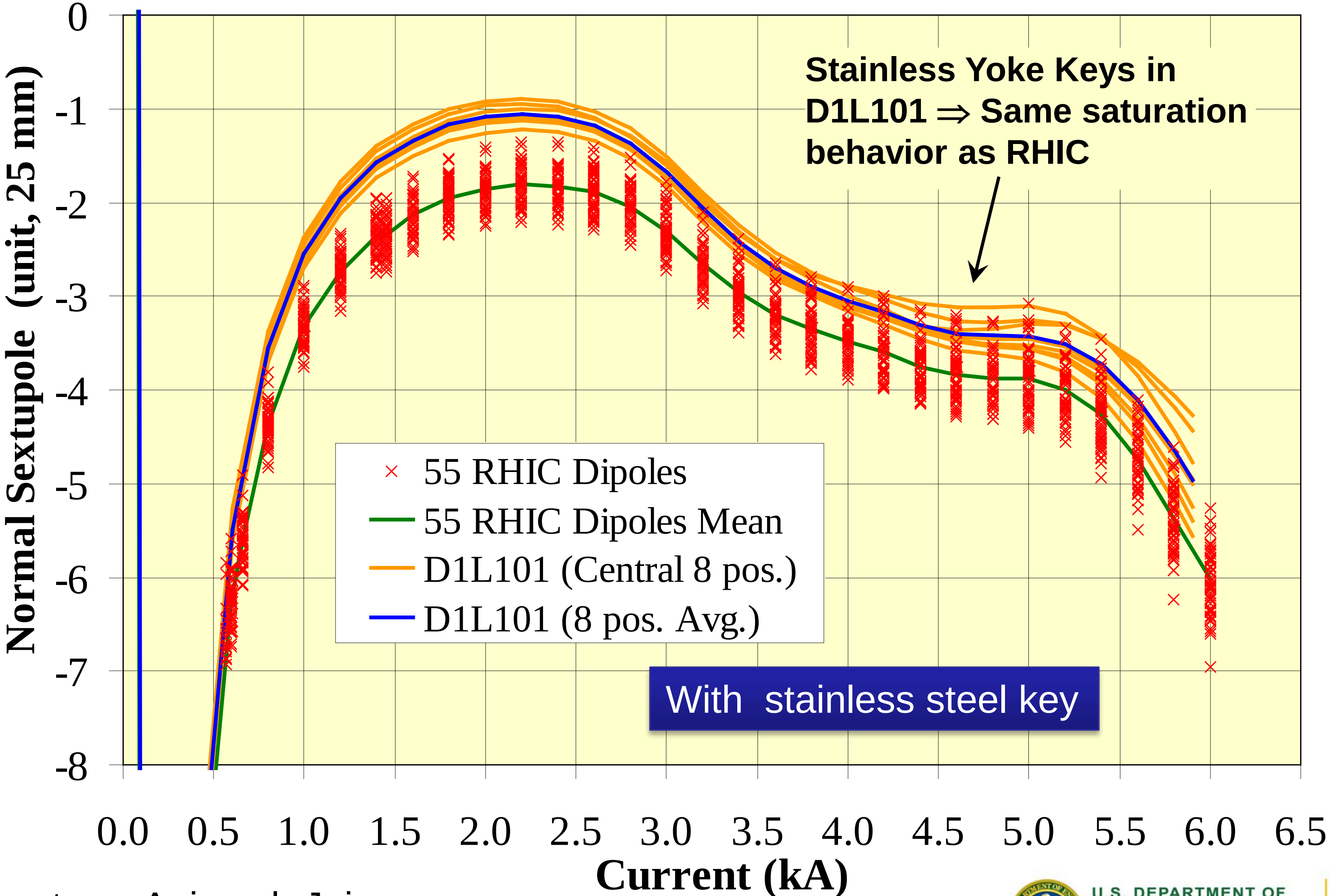




Courtesy: Animesh Jain



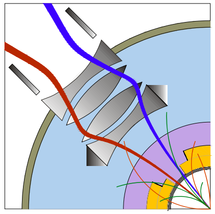
Warm-Cold Offsets in D1L101 & RHIC Dipoles



Courtesy: Animesh Jain

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

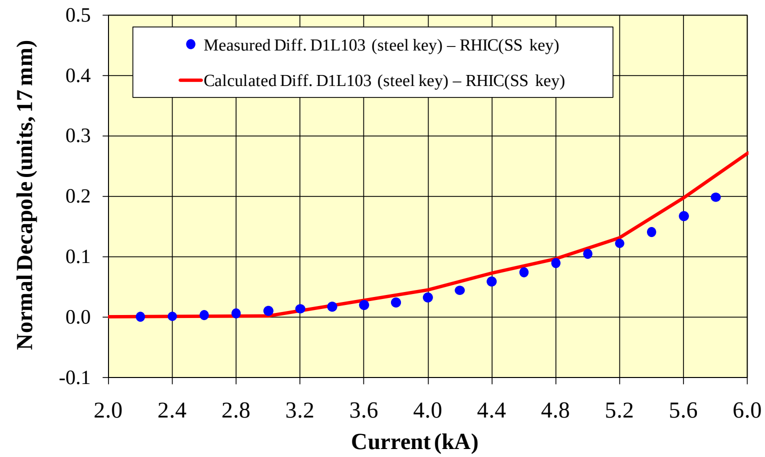
(Reference radius = 17 mm)



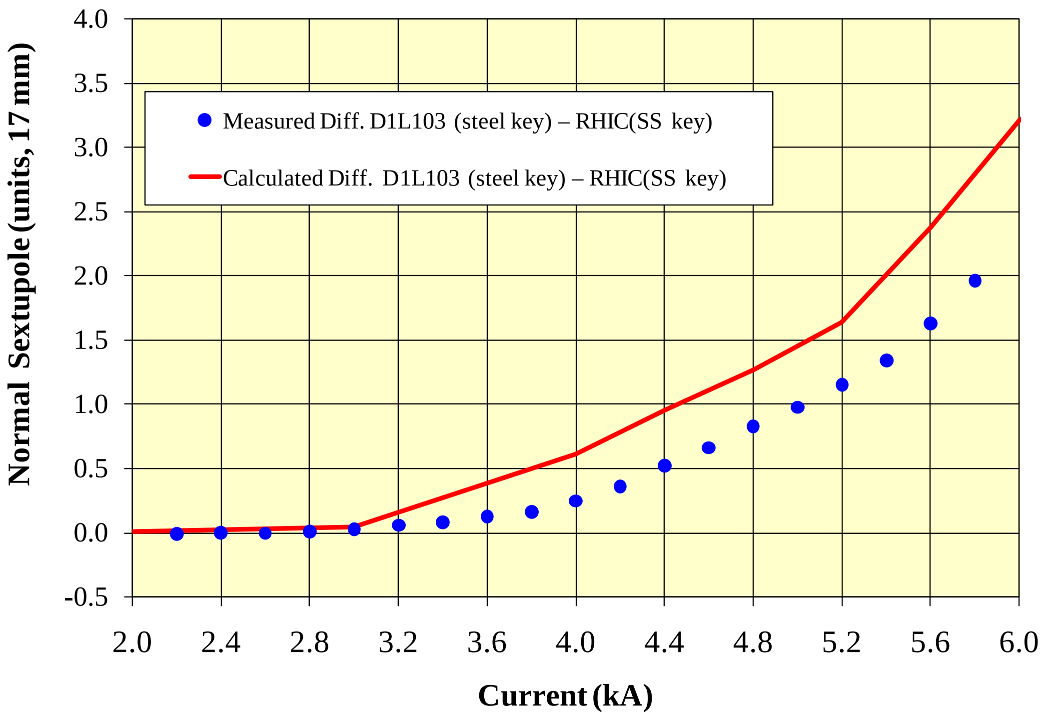
- Calculations assumes magnetic properties of steel key to be as good as that of yoke steel.

- This is not realistic and hence expect the change to be an over-estimate.

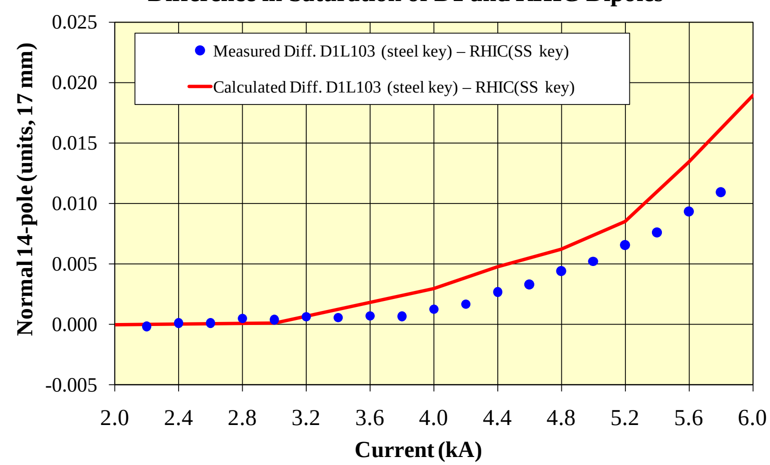
Difference in Saturation of D1 and RHIC Dipoles



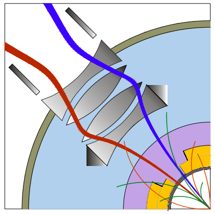
Difference in Saturation of D1 and RHIC Dipoles



Difference in Saturation of D1 and RHIC Dipoles



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)

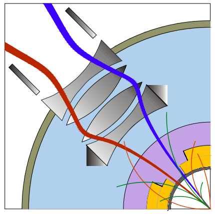
Actual operating temperature is 1.9K, which will impact the sextupole at injection significantly

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

Courtesy: Animesh Jain

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

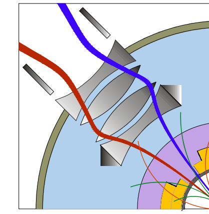
All harmonics are in units of 1E-4 at a reference radius of 25 mm. (January 27, 2004 version)

	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

Courtesy: Animesh Jain

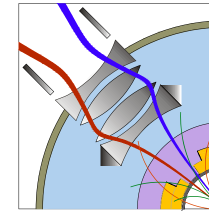
Measured and Expected (V 1.0) Harmonics in D1L Magnets

Integral Harmonics (units) at 25 mm reference radius



Harm.	Mean Values at 350A				Mean Values at 5600A				Standard Deviation			
	D1L Estim.	V 1.0		Comp.	D1L Estim.	V 1.0		Comp.	D1L Wm	Ver. 1.0		Comp.
		Min.	Max.			Min.	Max.			0.2 T	3.8 T	
b2	-0.08	-0.66	0.88	OK	-0.13	-0.54	1.05	OK	0.49	0.28	0.28	??
b3	-14.84	-16.78	-5.73	OK	-2.42	-5.27	1.86	OK	1.47	1.95	1.70	OK
b4	0.20	-0.24	0.15	??	0.19	-0.14	0.29	OK	0.12	0.08	0.08	??
b5	0.50	-0.21	1.45	OK	1.13	-0.56	1.03	??	0.15	0.40	0.39	OK
b6	0.04	-0.09	0.08	OK	0.06	-0.22	-0.02	??	0.06	0.03	0.04	??
b7	-0.42	-0.48	-0.06	OK	1.19	0.97	1.36	OK	0.07	0.10	0.10	OK
b8	-0.02	-0.07	0.00	OK	-0.01	-0.05	0.02	OK	0.02	0.01	0.01	OK
b9	0.02	0.02	0.27	OK	-0.07	-0.11	0.13	OK	0.04	0.04	0.04	OK
b10	0.03	-0.02	0.08	OK	0.03	-0.01	0.09	OK	0.02	0.02	0.02	OK
b11	-0.75	-0.71	-0.62	??	-0.69	-0.64	-0.56	??	0.01	0.02	0.02	OK
a2	-1.39	-3.77	3.59	OK	-3.38	-3.17	4.25	??	2.25	1.53	1.51	??
a3	-0.88	-1.59	-0.61	OK	-0.85	-1.86	-0.76	OK	0.12	0.17	0.18	OK
a4	-0.15	-1.03	1.27	OK	-0.61	-1.02	1.13	OK	0.68	0.42	0.41	??
a5	0.16	0.03	0.34	OK	0.16	-0.01	0.34	OK	0.09	0.06	0.06	??
a6	0.10	-0.57	0.51	OK	0.06	-0.60	0.50	OK	0.15	0.15	0.16	OK
a7	-0.11	-0.17	-0.02	OK	-0.11	-0.16	-0.05	OK	0.03	0.02	0.02	OK
a8	0.03	-0.16	0.14	OK	0.04	-0.17	0.14	OK	0.03	0.05	0.05	OK
a9	0.01	-0.01	0.05	OK	0.02	-0.02	0.04	OK	0.02	0.01	0.01	OK
a10	0.07	-0.03	0.07	OK	0.06	0.00	0.08	OK	0.02	0.02	0.02	OK
a11	-0.01	-0.03	0.00	OK	-0.01	-0.03	0.00	OK	0.01	0.01	0.01	OK

Courtesy: Animesh Jain



FIELD QUALITY

- Same as US-LHC, except for limit on *normal sextupole*: $b_3 <$ 2 units at high field (3 of 4 D1's in LHC meet this criterion).
  - Unit = 10^{-4} of the dipole field (17 mm ref. radius).
  - RHIC magnets: $\sigma(b_3)$ = 0.9 "units" $\Rightarrow$ For APUL, will measure after collaring coils, change shims if necessary to achieve *geometric* (conductor placement) value
  - APUL, *high field*, may need to adjust *saturation*-control holes in yoke – will review calculations; option: iron rods in yoke holes.
- *Skew quadrupole*: same as US-LHC
  - Need two coils closely matched; choose from group of four.
- These are standard procedures to improve FQ.