Use of Warm Magnetic Measurements in Locating Electrical Shorts in Magnets

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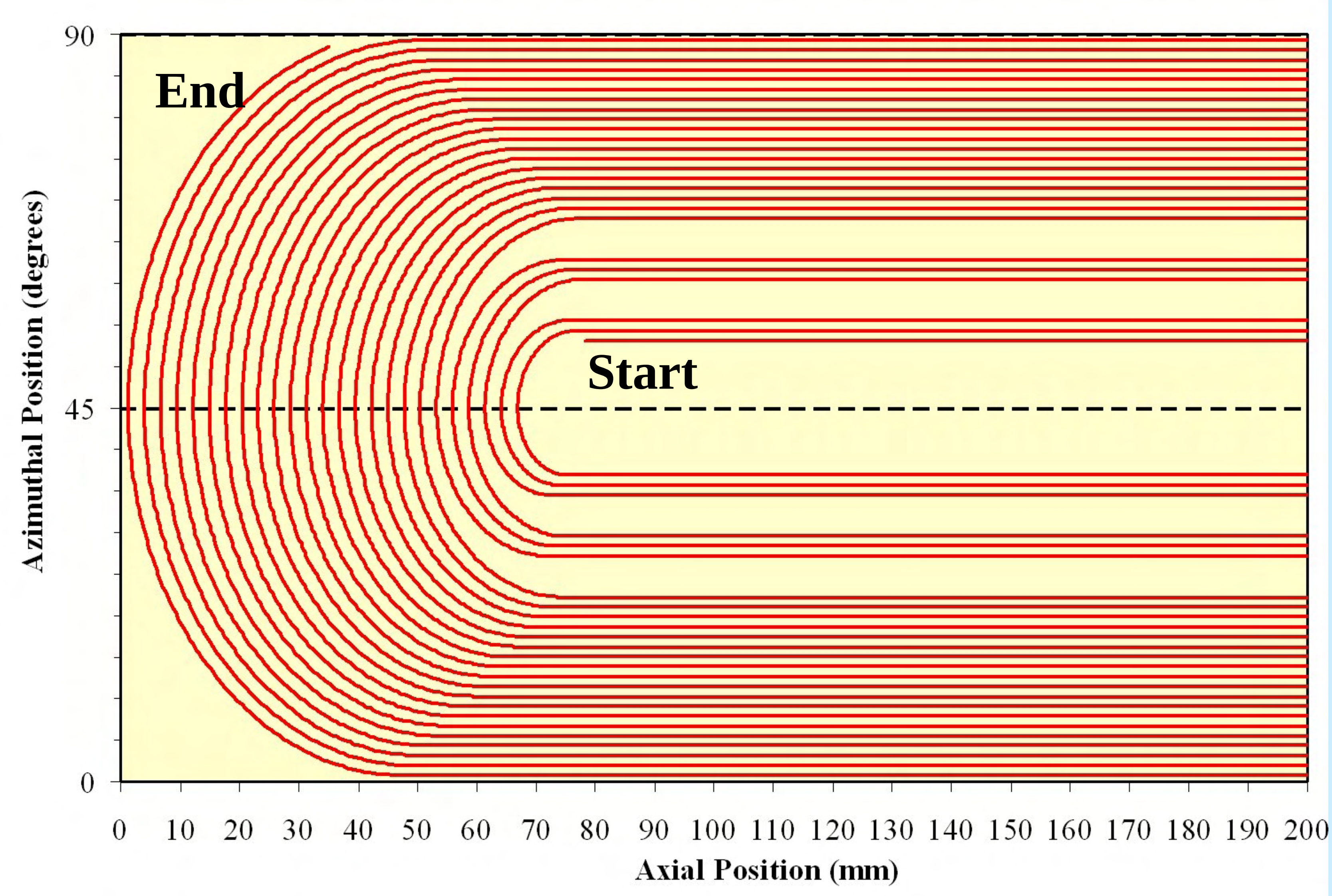
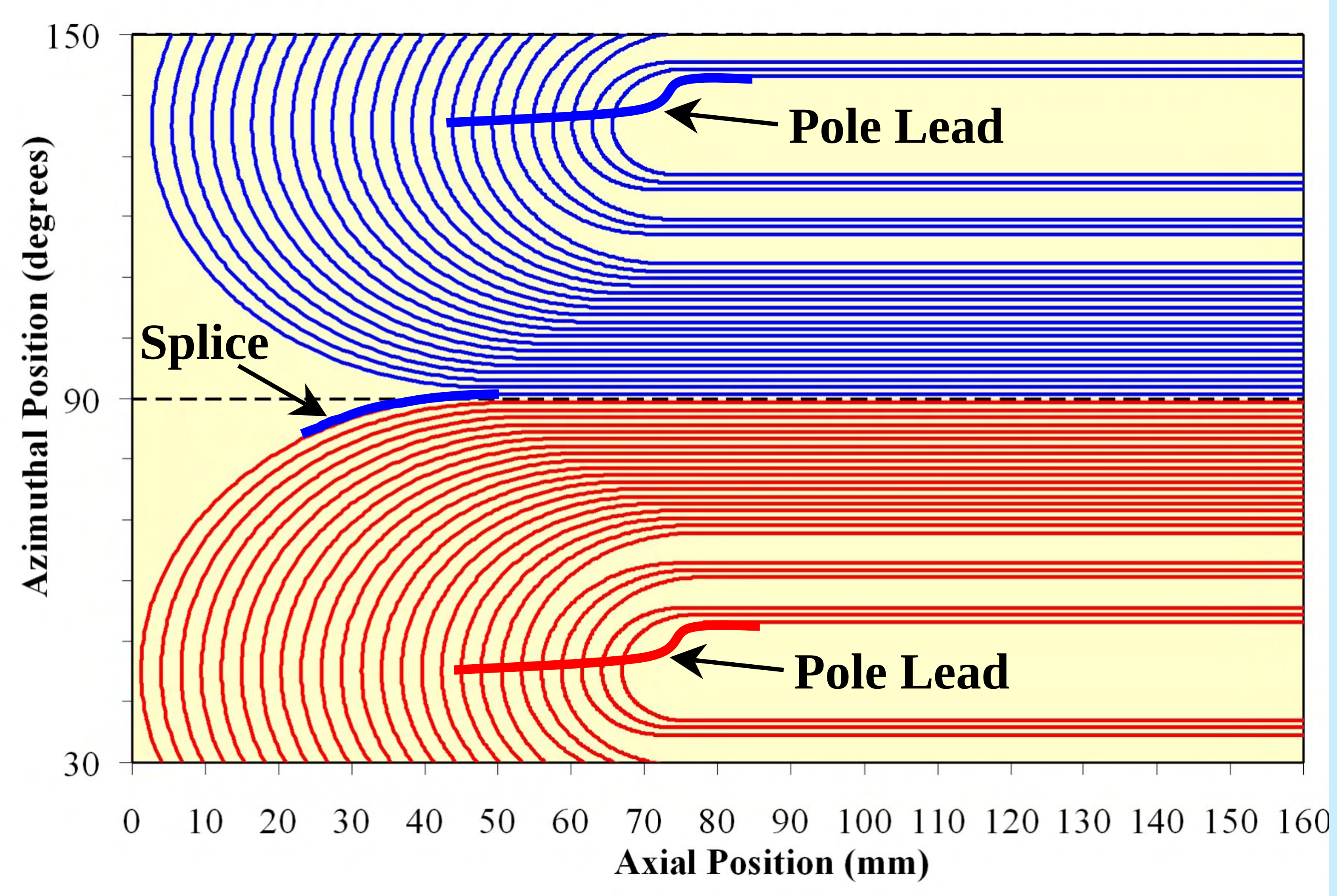
Introduction

- BNL has recently built several multi-layer magnets for the HERA luminosity upgrade program at DESY, Hamburg.
- These magnets were made by winding ~1 mm dia. cable directly on a support cylinder, using an automatic machine.
- Each layer had to be cured, and various “sub-coils” had to be spliced. This could lead to electrical shorts and errors.
- Extensive warm measurements were carried out at various stages of production to ensure quality control.
- On a couple of occasions, large changes in harmonics were observed after subsequent production steps. These were shown to result from electrical shorts at specific locations, leading to a relatively simple repair of the magnets.

A Typical Quadrupole "Sub-coil"



Splice Between “Sub-coils”



QH0101: Quad Layer 2

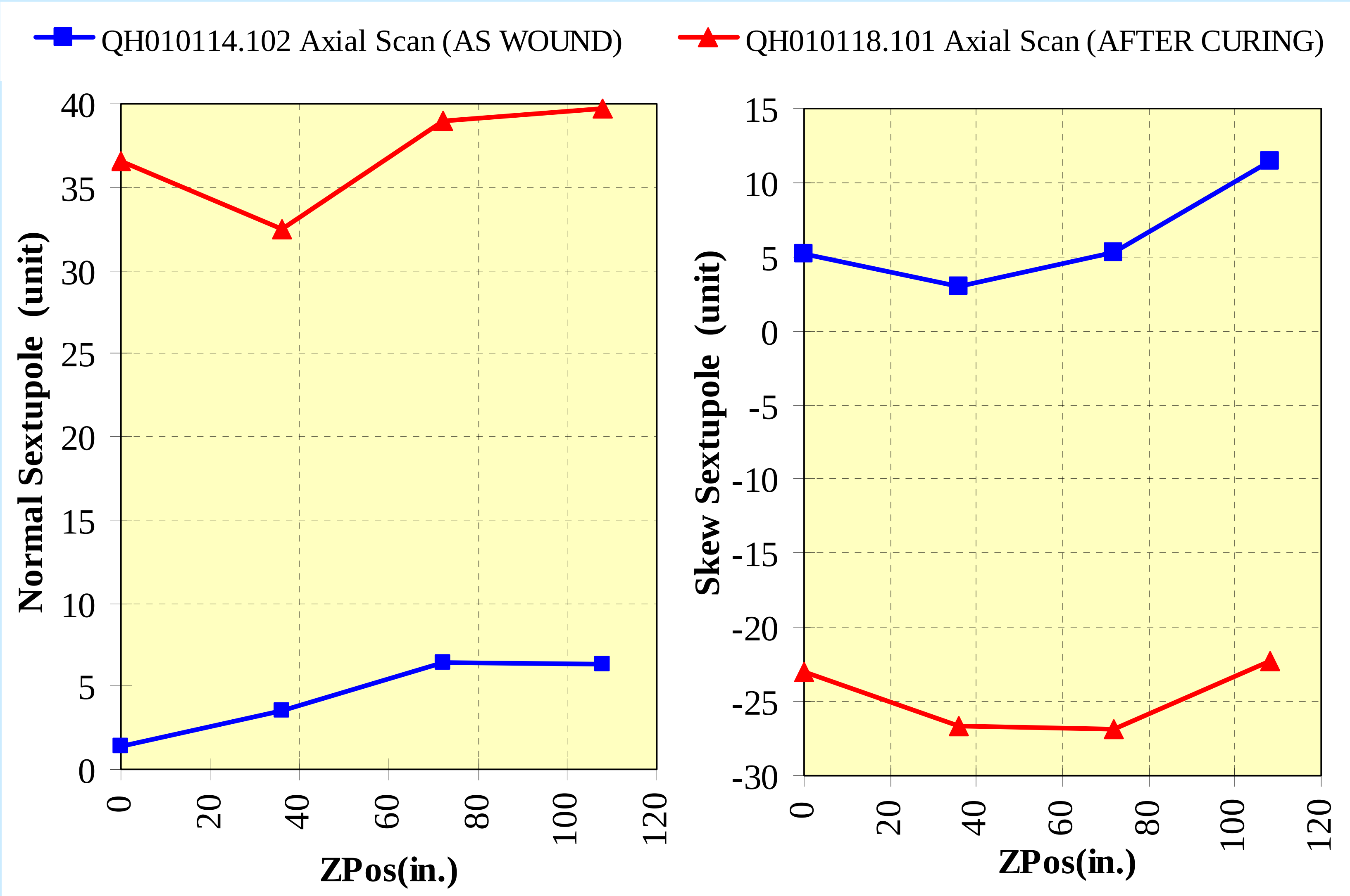
The magnet QH0101 showed large changes in harmonics in the second quadrupole layer after curing. Since warm measurements were made after each step in the early stages of the program, the changes were immediately detected.

	as wound	wrap & cure	Change
T.F.(T/m/kA)	8.6446	8.5790	**-0.76%**
b3	4.99	35.72	**30.73**
b4	-14.55	-14.25	**0.30**
b5	-1.98	5.65	**7.63**
b6	2.87	-5.66	**-8.53**
b10	0.22	-0.40	**-0.63**
a3	4.15	-26.75	**-30.90**
a4	2.96	3.20	**0.24**
a5	1.59	9.42	**7.83**
a7	-0.41	-2.61	**-2.19**

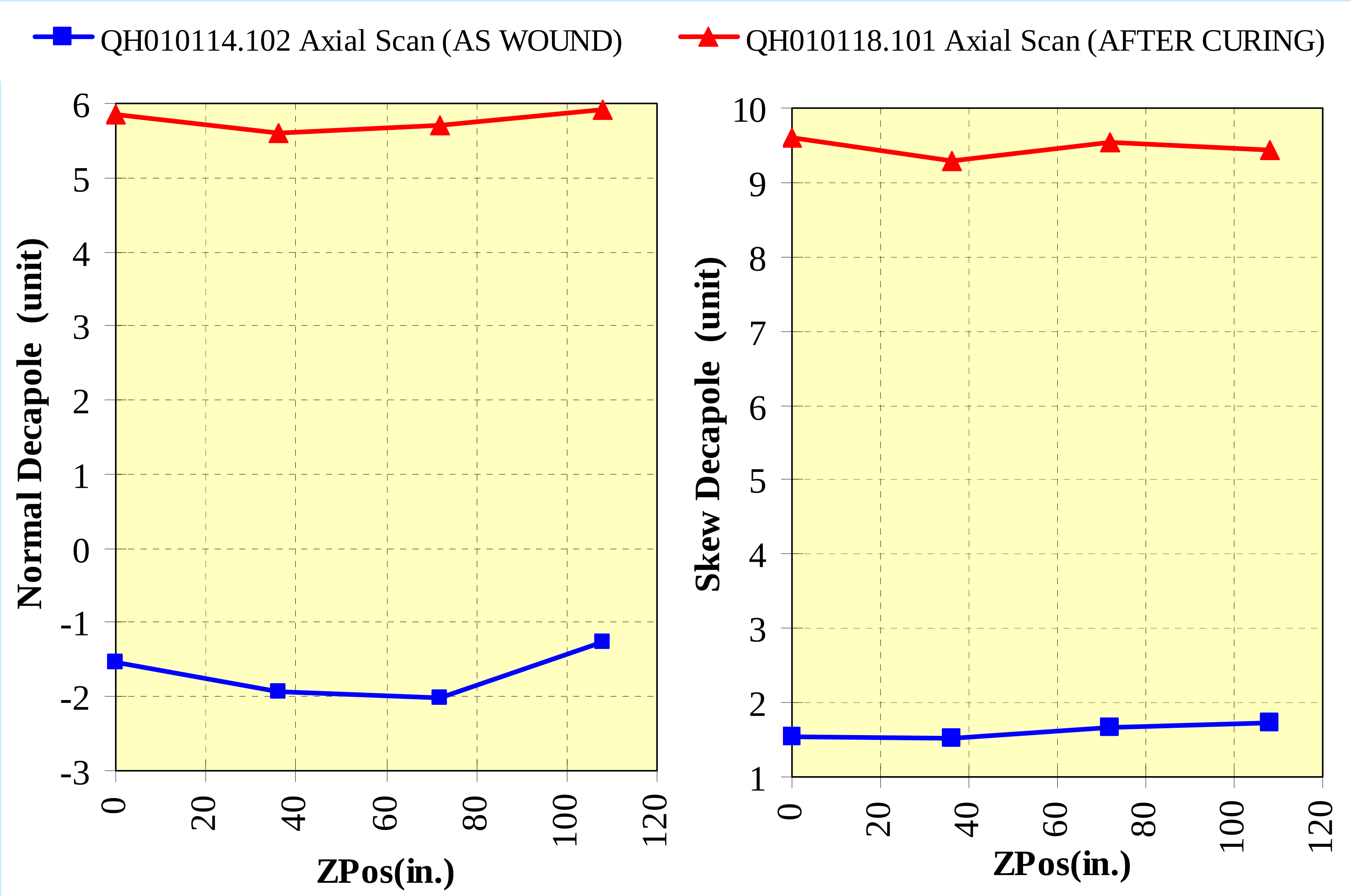
⇐ an increase was expected

Selected harmonics in “units” at 31 mm reference radius

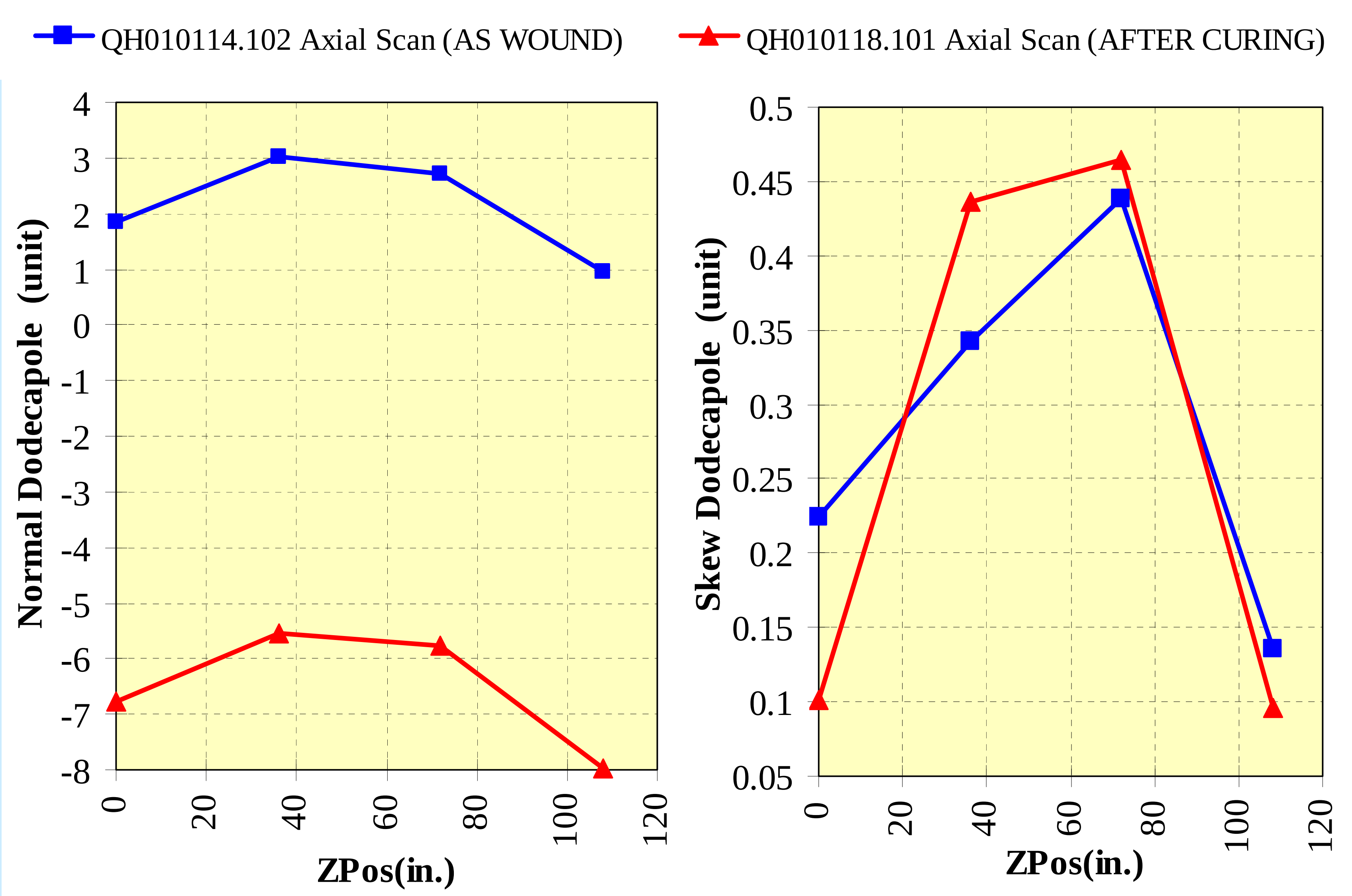
Axial Scans in QH0101: Q2 Layer



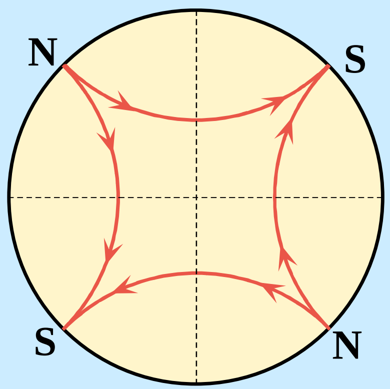
Axial Scans in QH0101: Q2 Layer



Axial Scans in QH0101: Q2 Layer



Determining the Problem Quadrant



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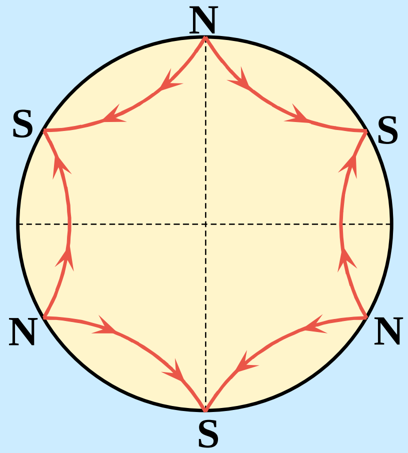
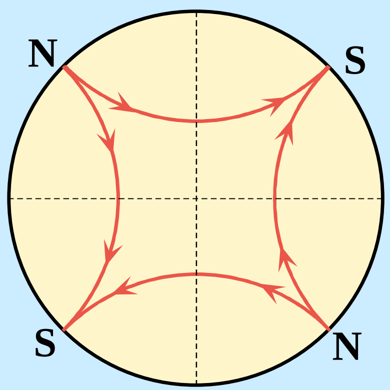


= Weaker field on left

Normal Quad

+ve Normal Sextupole



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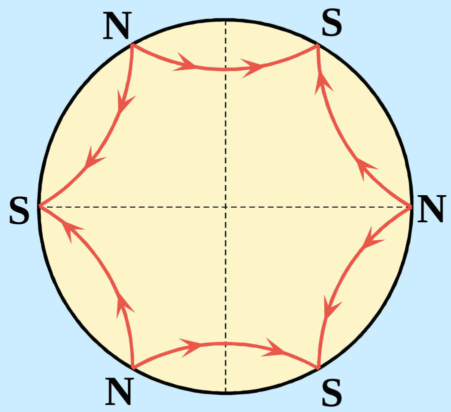


= Weaker field on bottom

Normal Quad

–ve Skew Sextupole

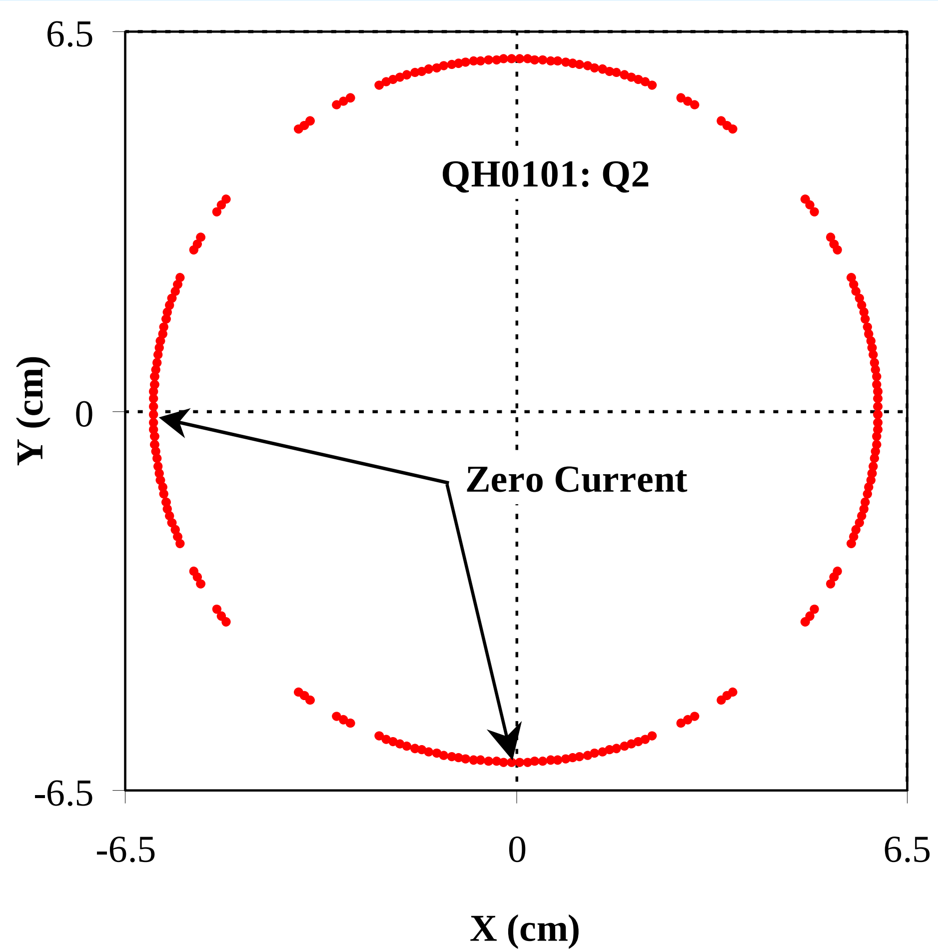
Missing Current in the 3rd Quadrant

QH0101: Quad Layer 2

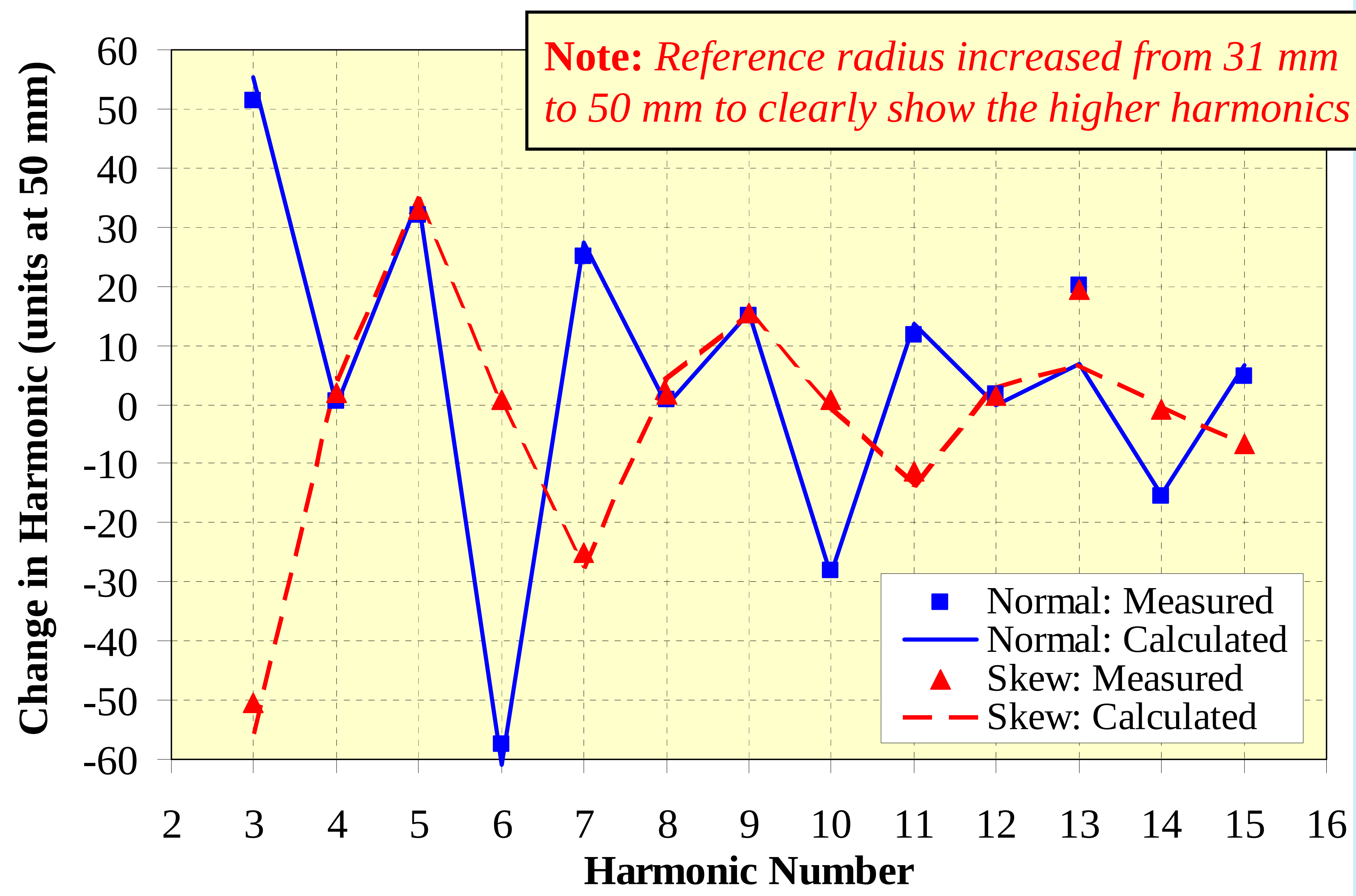
- Harmonic changes were too large.
- Transfer function was reduced, instead of showing an increase that was expected after curing.
- An axial scan showed essentially the same errors along the entire length, implying a problem at the ends.
- Positive normal sextupole and negative skew sextupole implied weaker field in the lower left region (the 3rd quadrant).
- Other harmonics could be used to pinpoint the location of the problem. However, the most likely place for an electrical short at the ends was at the midplane splice.

Modeling Field Quality with a Short

- Most likely area: splice from one sub-coil to the next.
- Would bypass current from the outermost turn.



Computed Vs Measured Changes



Repair of QH0101 (Q2 Layer)

- The excellent agreement between the calculated and the measured harmonics confirmed the presence of an electrical short at the midplane splice in the 3rd quadrant (between the 3rd and the 4th sub-coils).
- Since no further layers were yet wound on the magnet, the repair was relatively simple.
- Measurements after the repair confirmed that the harmonics returned to their original values.
- Later on in the production, two sub-coils were wound in a continuous pattern (spiral out, followed by spiral in), eliminating the need for a midplane splice.

Another Example: QH0103

- Large changes in the harmonics were also observed in the main quadrupole of the magnet QH0103 after all the layers were completed. These changes did not appear as dramatic as were shown before, since the three quadrupole layers were only measured in series, but were still much larger than usual.
- At this stage in production, magnetic measurements were not carried out after each step. So, it was difficult to judge at what step the problem could have occurred.
- There could have been a problem with any of the three main quadrupole layers, which were now buried under one skew dipole/skew quadrupole layer and one sextupole layer. The layers outside the quadrupole alone represented ~ 3 months of work.

QH0103 Diagnostics

- All three quadrupole layers were connected in series, making it difficult to measure individual layers.
- Warm measurements on individual layers were carried out at a very low current of 0.25A utilizing the voltage taps between the layers as current leads.
- These measurements revealed practically no changes in the first and the third quadrupole layer, but showed large changes in harmonics of the second layer. These changes were about as large as were seen earlier in the case of QH0101.
- The low current warm measurements thus clearly established a problem with the second quadrupole layer.
- Interestingly, there did not appear to be much loss of transfer function in the Q2 layer. This suggested that the problem was more likely to be in the pole region, than in the midplane region.

Harmonic Changes in QH0103:Q2

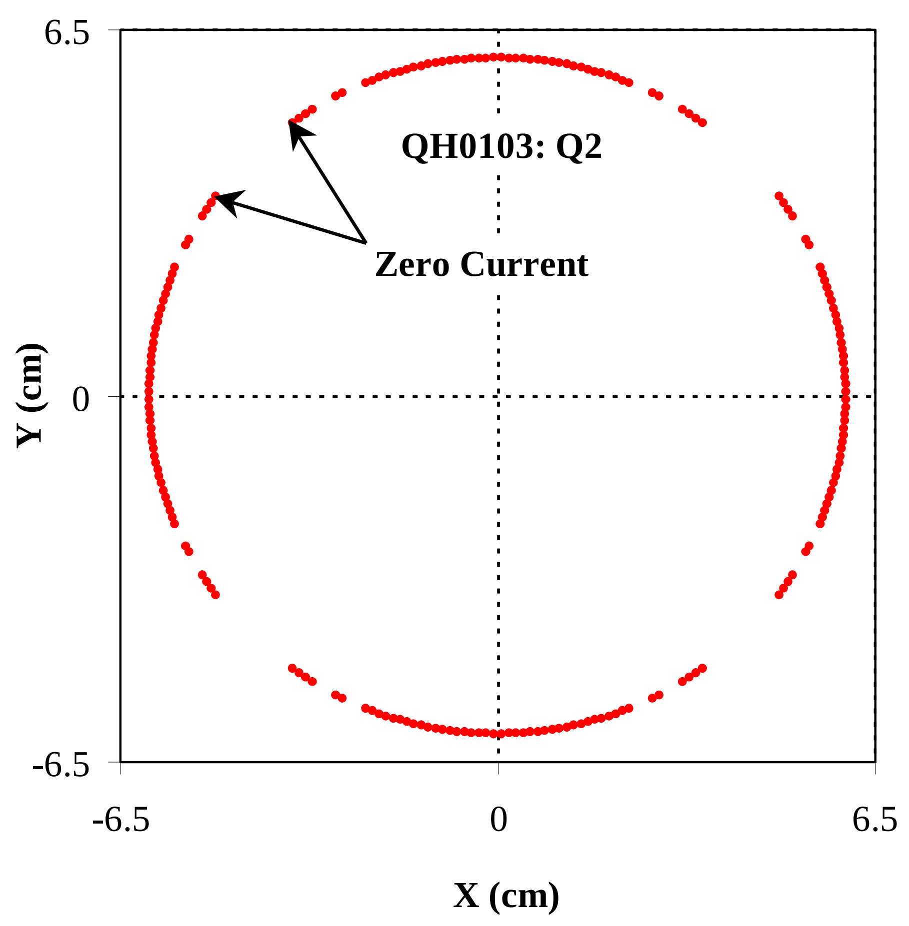
	as wound	final meas.	Change
T.F.(T/m/kA)	8.6534	8.6956	**0.49%**
b3	-2.91	16.47	**19.37**
b4	0.77	1.39	**0.62**
b5	-0.50	-7.82	**-7.32**
b6	-0.98	5.66	**6.64**
b7	-0.19	-2.81	**-2.62**
a3	-1.82	16.71	**18.52**
a4	-4.12	-21.69	**-17.57**
a5	-0.12	7.77	**7.89**
a7	-0.16	-2.64	**-2.47**

⇐ increase expected

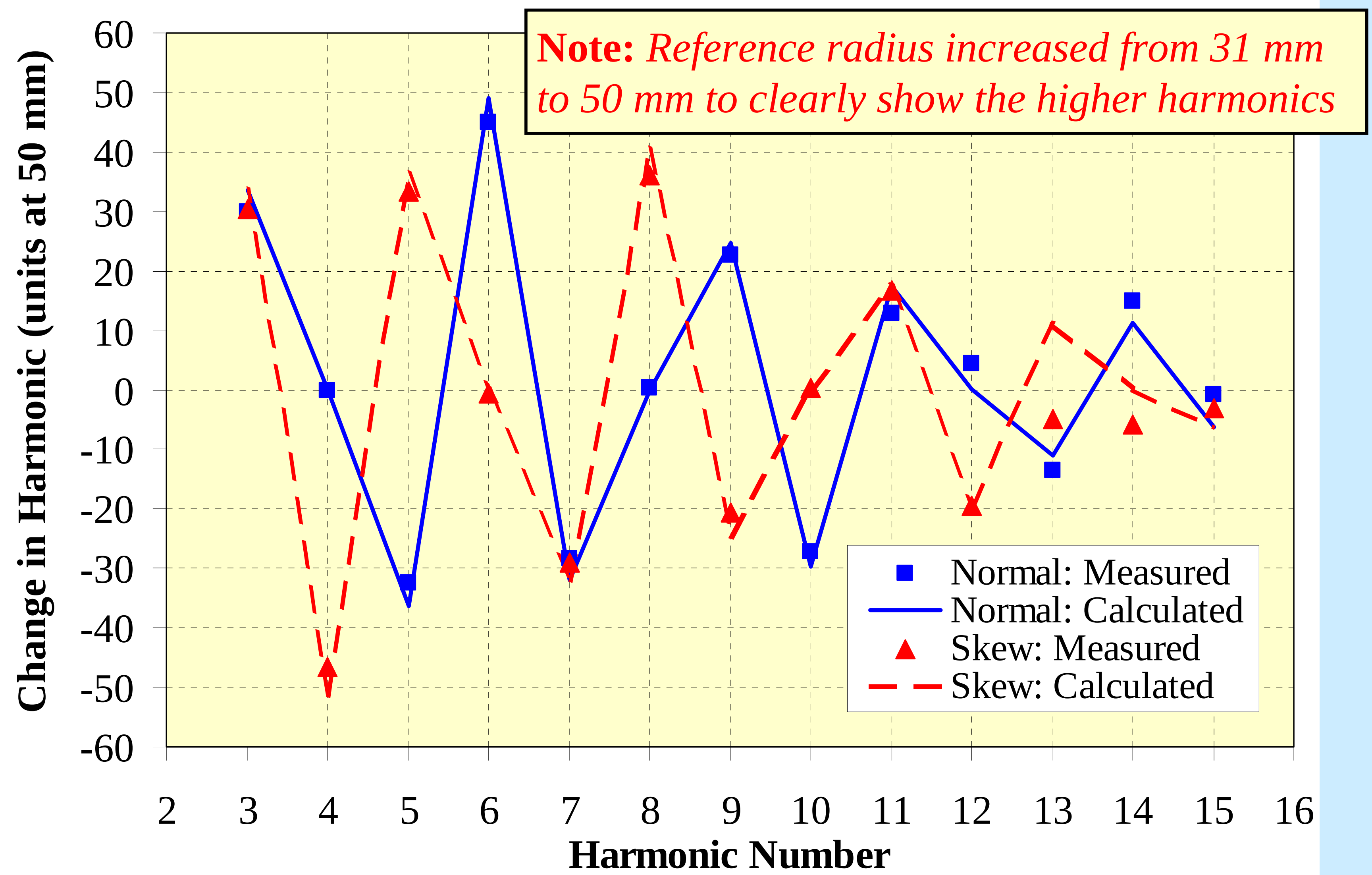
Selected harmonics in “units” at 31 mm reference radius

Modeling Field Errors in QH0103

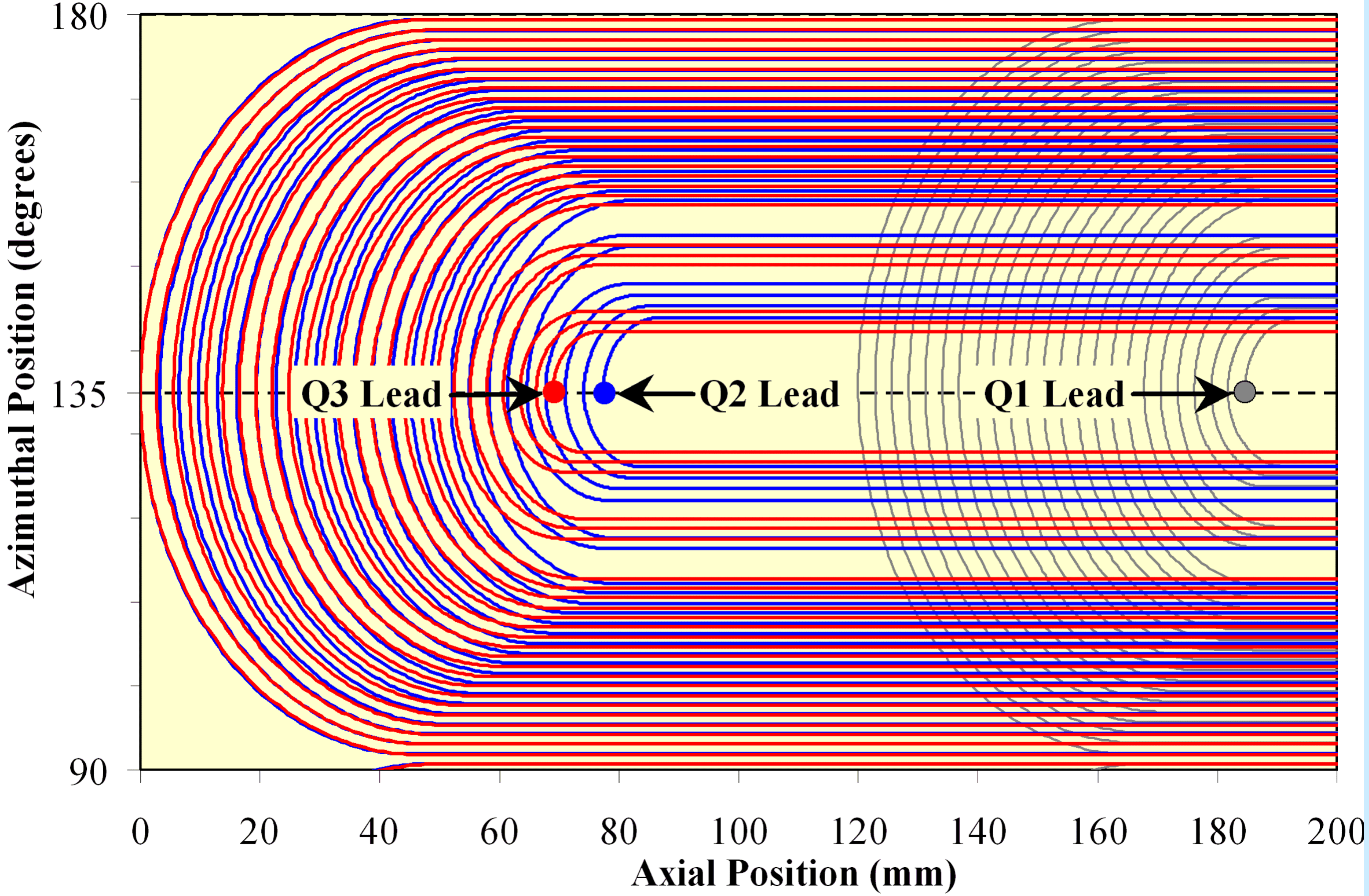
- Most likely area: pole lead in the 2nd quadrant.
- Would bypass current from the pole-most turn.



Computed Vs Measured Changes

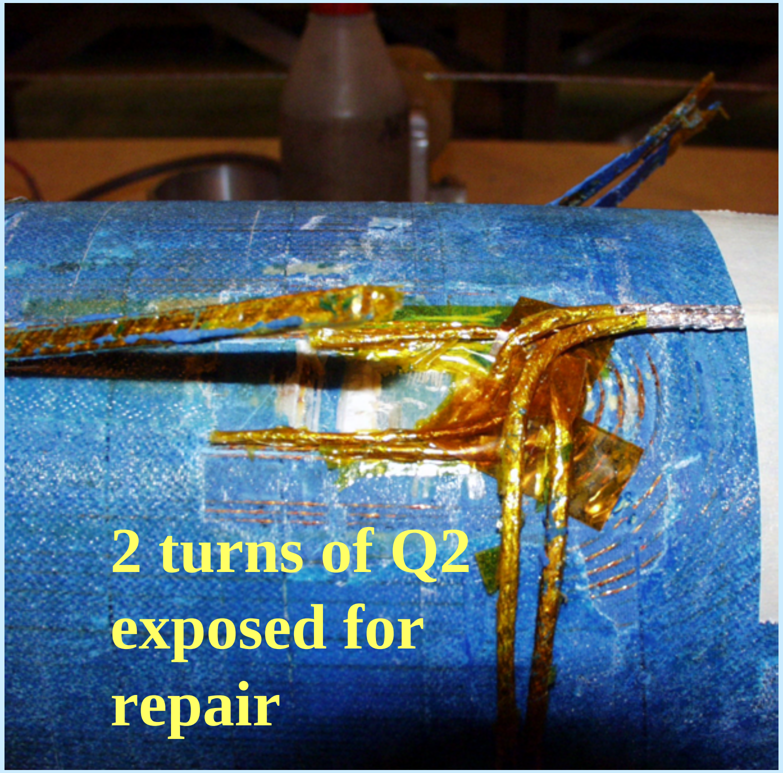


QH0103: Q1, Q2, Q3 Layers



QH0103: Repair of Q2 Short

Fortunately, it was possible to carefully cut into the S-glass wrap to reach the pole lead of Q2, without affecting other layers. Thus, a repair could be performed without sacrificing any layer.



Conclusions

- Warm measurements proved to be a very sensitive tool to monitor magnet production, consistent with earlier experiences at BNL and elsewhere.
- Accurate harmonic information, coupled with a model analysis, provided exact location of electrical shorts.
- The available information was used effectively to carry out repairs without the need to sacrifice other layers, thus saving considerable amount of time and effort.