Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Cross section analysis of HQ magnets

Summer Student Internship – Final presentation

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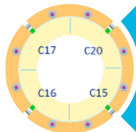
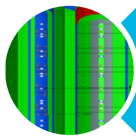
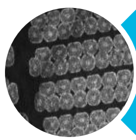
Outline



The big picture

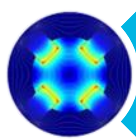


Our tasks



Turn location measurement process

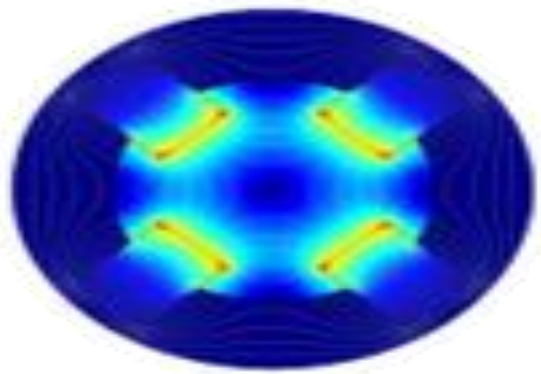
Coil cross section database

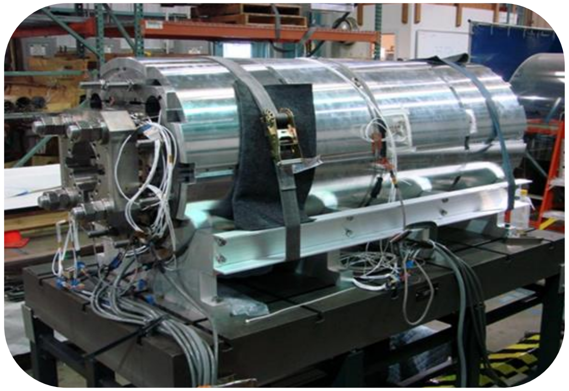


Impact on field quality

Future work

The big picture





Superconducting Nb_3Sn quadrupoles for Hi-Lumi LHC

Main goal: Ensure adequate field quality

HQ test magnets

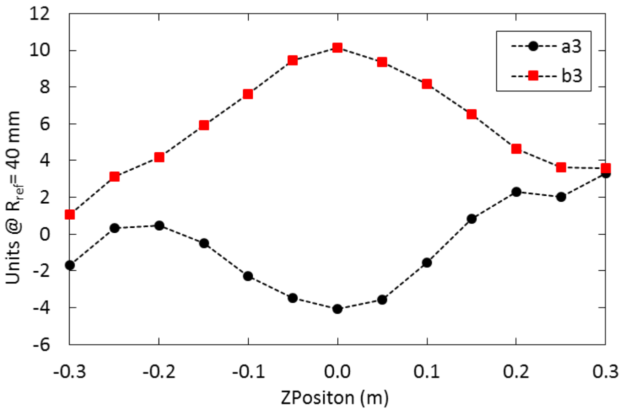
The big picture

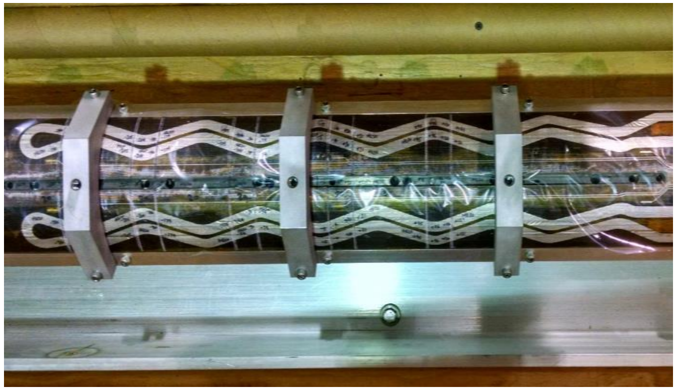
HQ magnets are designed (turn locations, iron, …) to provide a quadrupole field

Asymmetries in the magnets cause undesired higher order harmonics in magnetic field

Identify the drivers (turn displacement, iron or coil asymmetries, differential contraction or preload, …)

We focused on conductor locations in the magnet





From 3D to 2D

Analysis of field quality is a 3D problem

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HQ magnets have high length/cross section ratio

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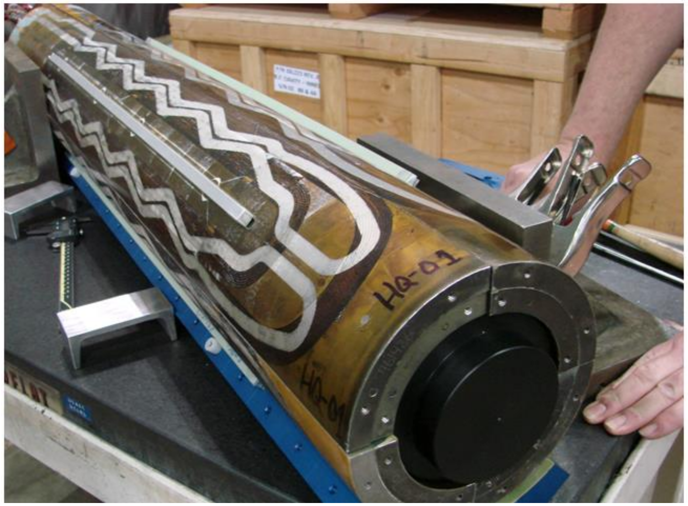
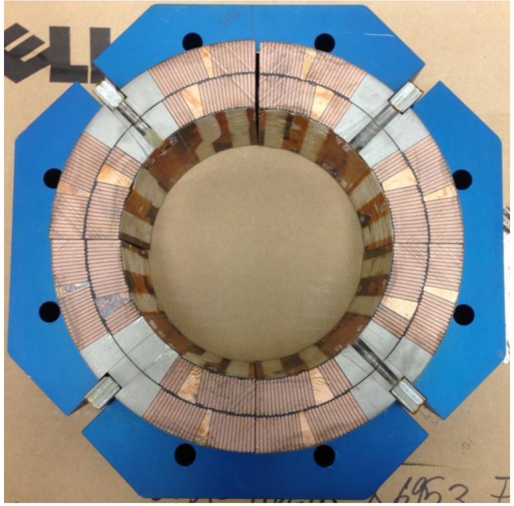
HYPOTHESES: Field quality in central cross sections depends only on 2D features (turn locations, poles, iron, …)

↓

Focus on magnet cross sections





The program

Measuring magnetic field at different locations along the magnet

Water-jet cutting the 4 coils at the cross sections showing higher discrepancy to expected field

Measuring turn locations on each coil segment

Simulating magnetic field with actual turn locations

Comparing numerical results with experimental ones

Expected goals

Quantify the role of turn location in field quality perturbations

Identify other drivers of poor field quality

Forecast issues for next generation magnets (QXF)

Get useful information to improve the magnet fabrication process

Our task

Developing a process for measuring turn location with an Optical Comparator (accuracy and repeatability)

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Collect data (both for single coils and fully assembled cross sections)

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Develop MATLAB tools to process, show and store data

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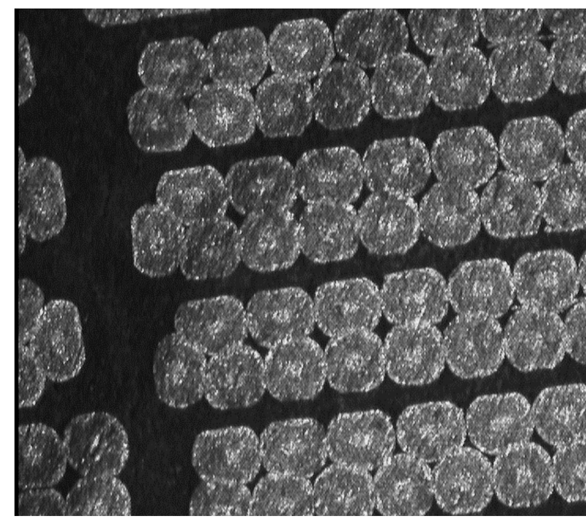
Use coil data as an input to a magnetic field simulation model

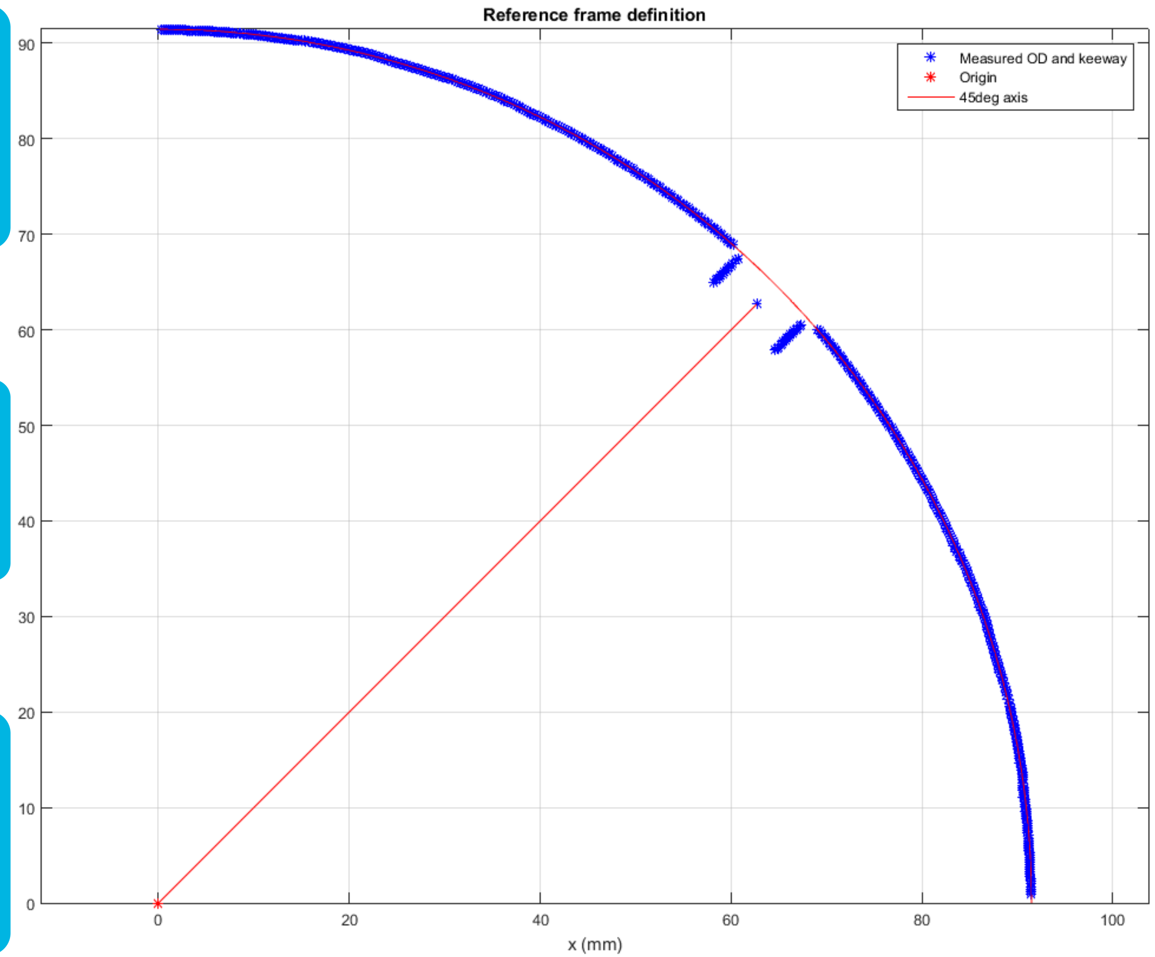


Measurement process - 1

DEFINE A REFERENCE FRAME

Best fit coil outer diameter to find origin

Keyway sides define the 45° axis



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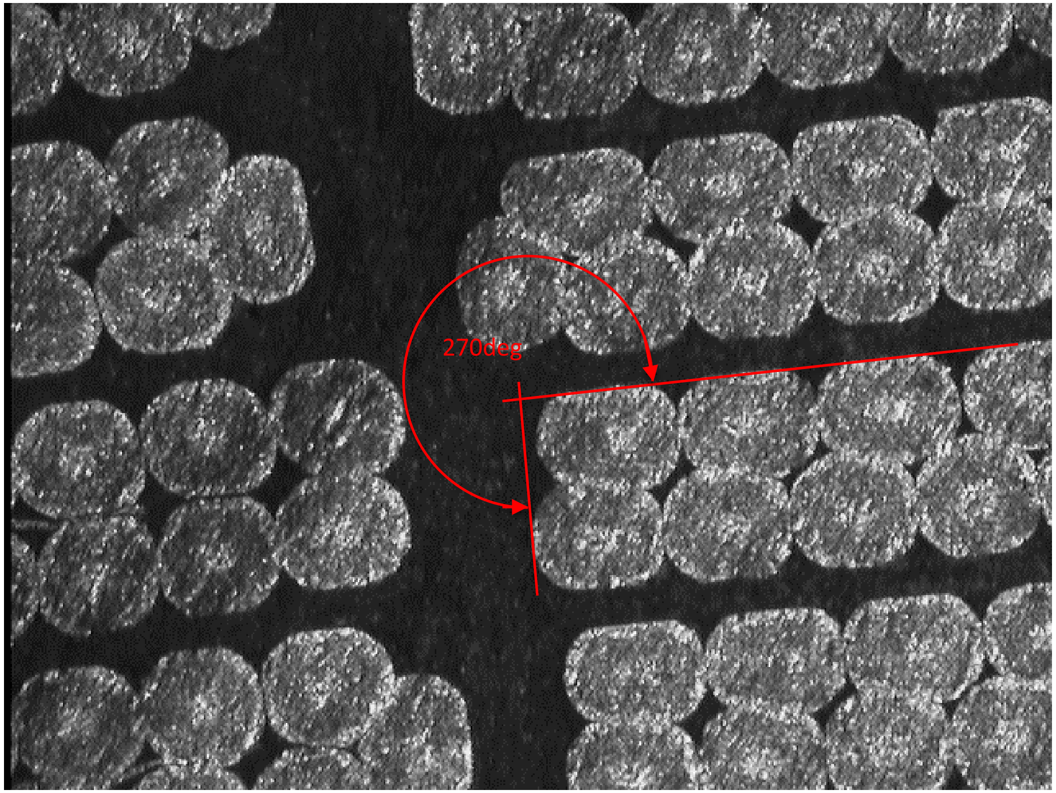
Measurement process - 2

IDENTIFY THE FOUR TURN CORNERS

Use perpendicular construction lines

Accommodate to the strand edges



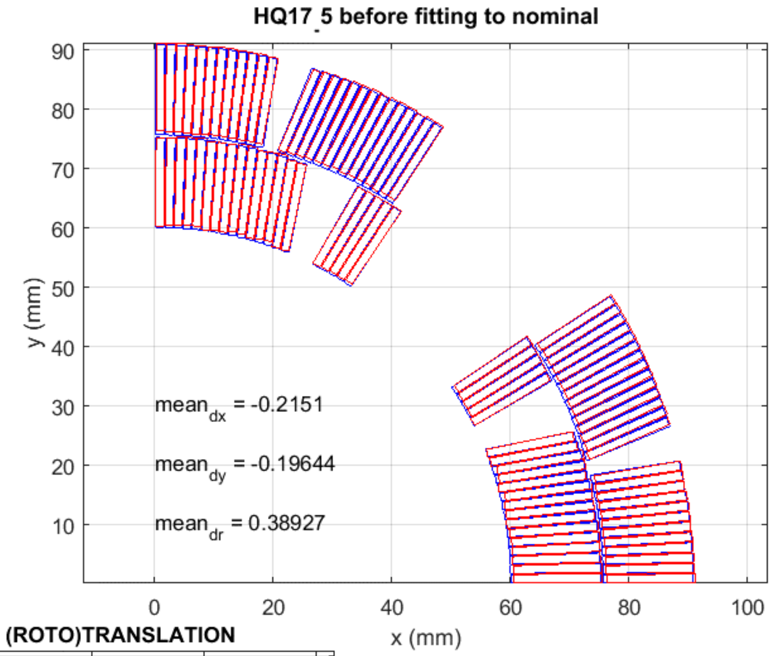
Measurement process - 3

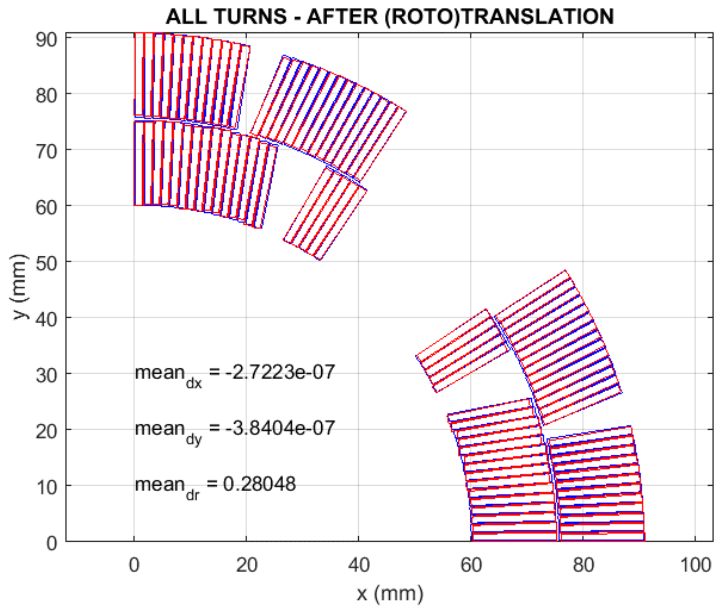
An accurate and repeatable process is needed to compare turn locations in different cross sections

The OD surface for each cross section varies too much for the needed accuracy.

ADJUST POINT TO BEST FIT NOMINAL

Translate and rotate points to minimize a residual wrt nominal





HQ17@ -5

X0 = -.2088 mm

Y0 = -.2027 mm

ϑ = -.00013 rad

Like simply translating!!

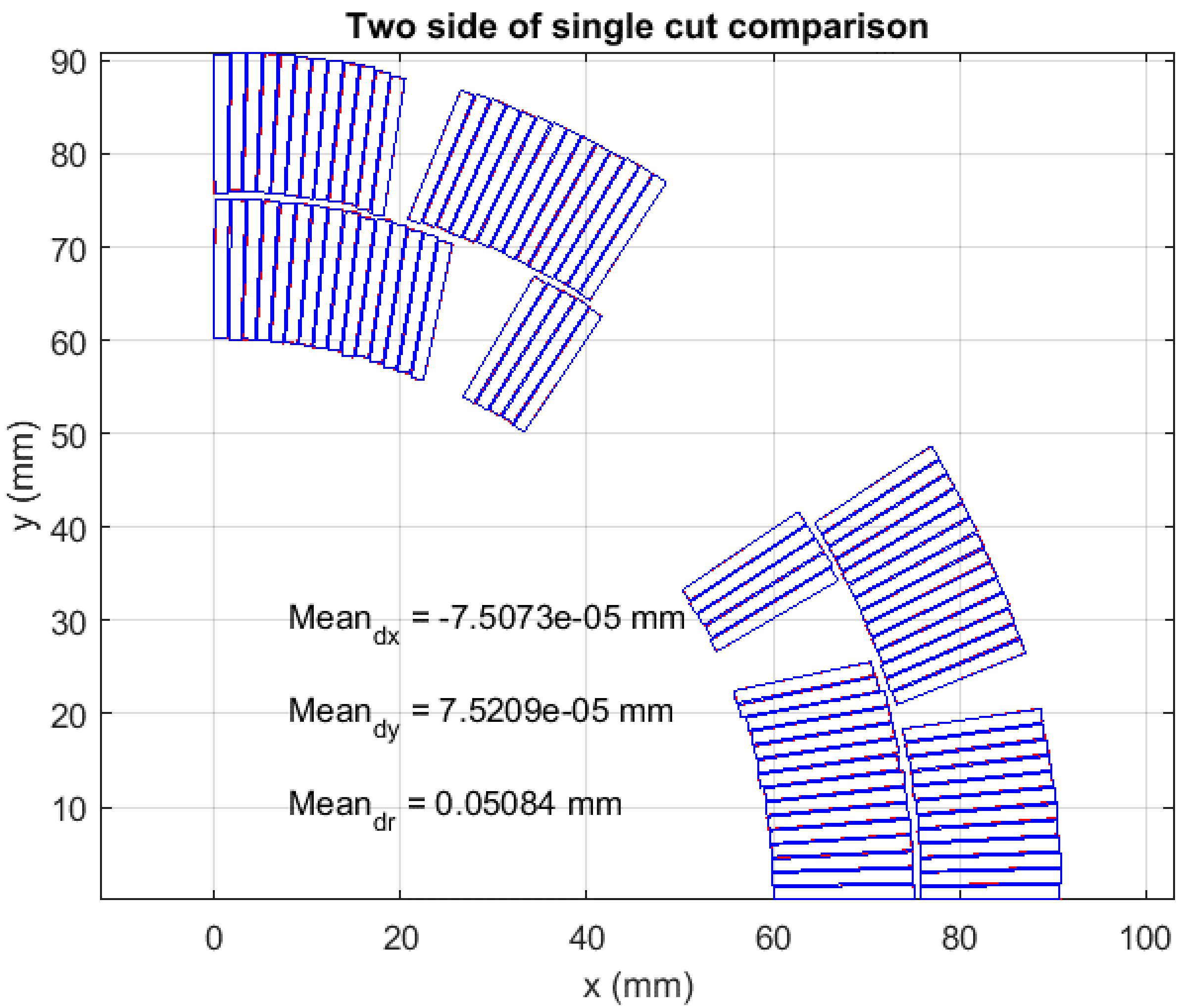
Measurement process validation

Collect turn location data for two sides of a single cut of HQ20 coil

Flip points of trailing end about 45° axis

Error in x and y direction cancel out almost completely

Mean distance between points: 0.05 mm



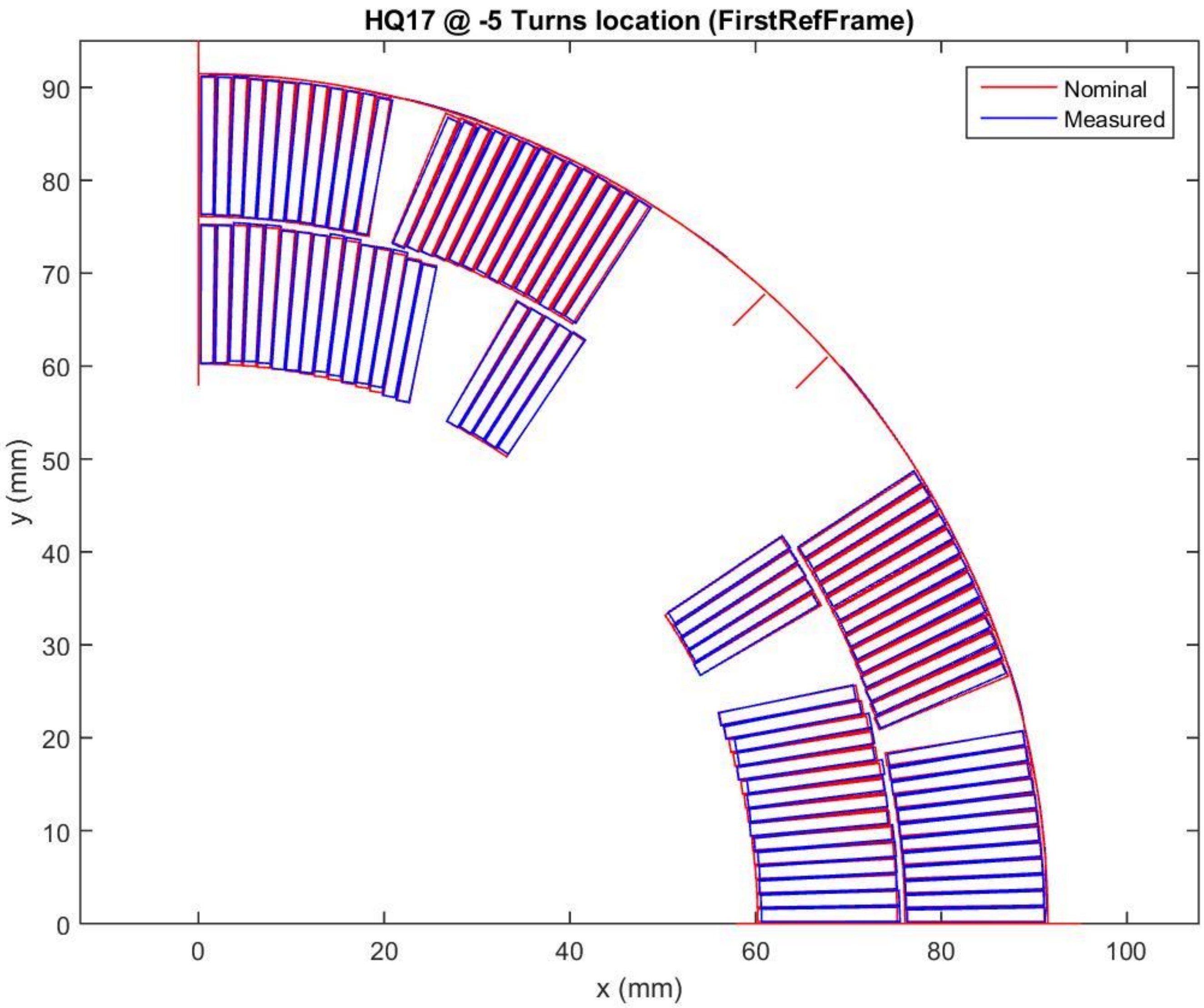
Measurement process – strengths and weaknesses

- Process tested for accuracy and repeatability assessing the same coil cross section a number of times

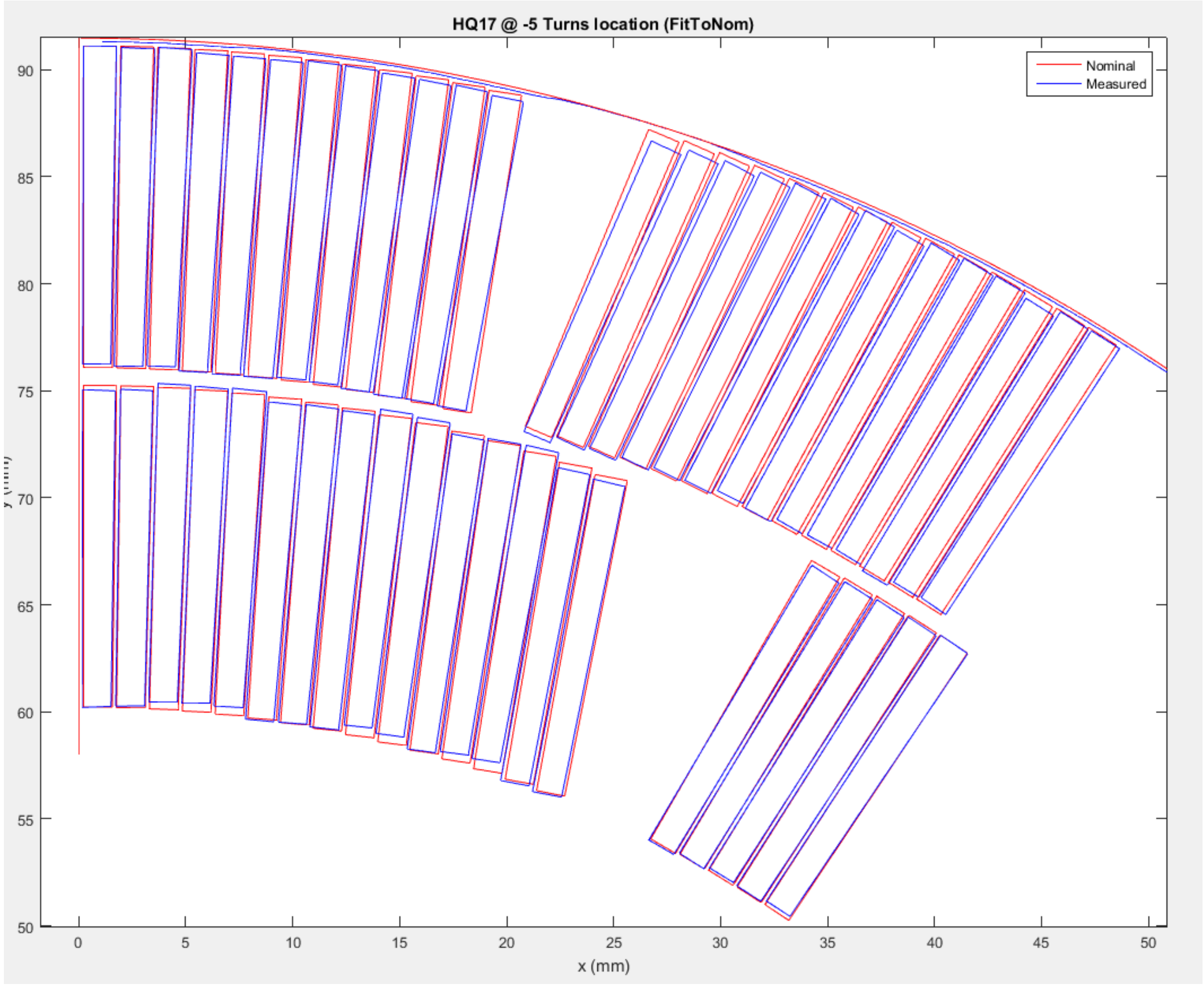
- Systematic error: <0.003 mm
  - Based on accuracy of the OGP comparator equipment
  - No scaling or calibration error

- Random error: 0.012 mm
  - One sigma distance from average from repeated measurements of the same cross section

- Time consuming process - 1h30min per coil cross section


HQ17 @ -5 Turns location (FirstRefFrame)
Nominal
Measured
y (mm)
x (mm)
0
10
20
30
40
50
60
70
80
90
0
20
40
60
80
100

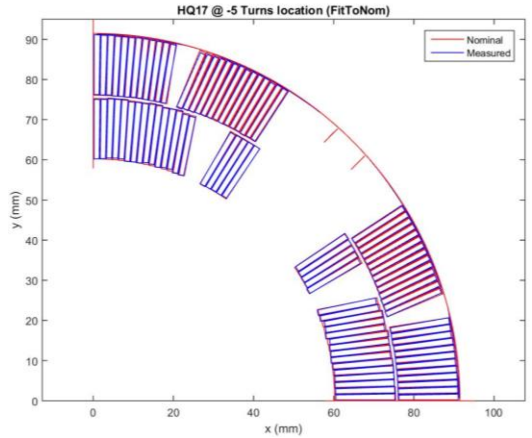
HQ17 @ -5

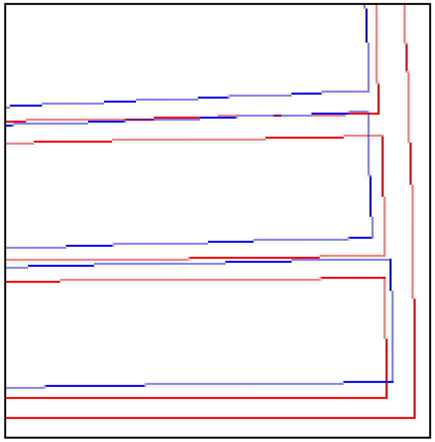


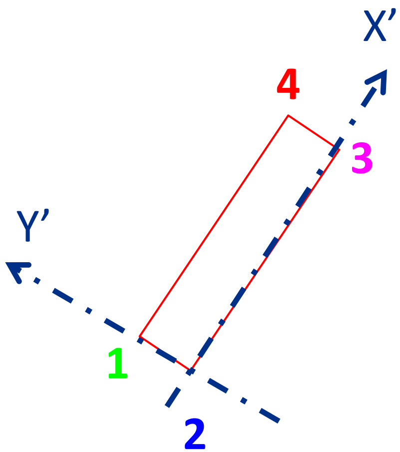
HQ17 @ -5 Turns location (FitToNom)
Nominal
Measured
90
85
80
75
70
65
60
55
50
0
5
10
15
20
25
30
35
40
45
50
x (mm)

Coil cross section database

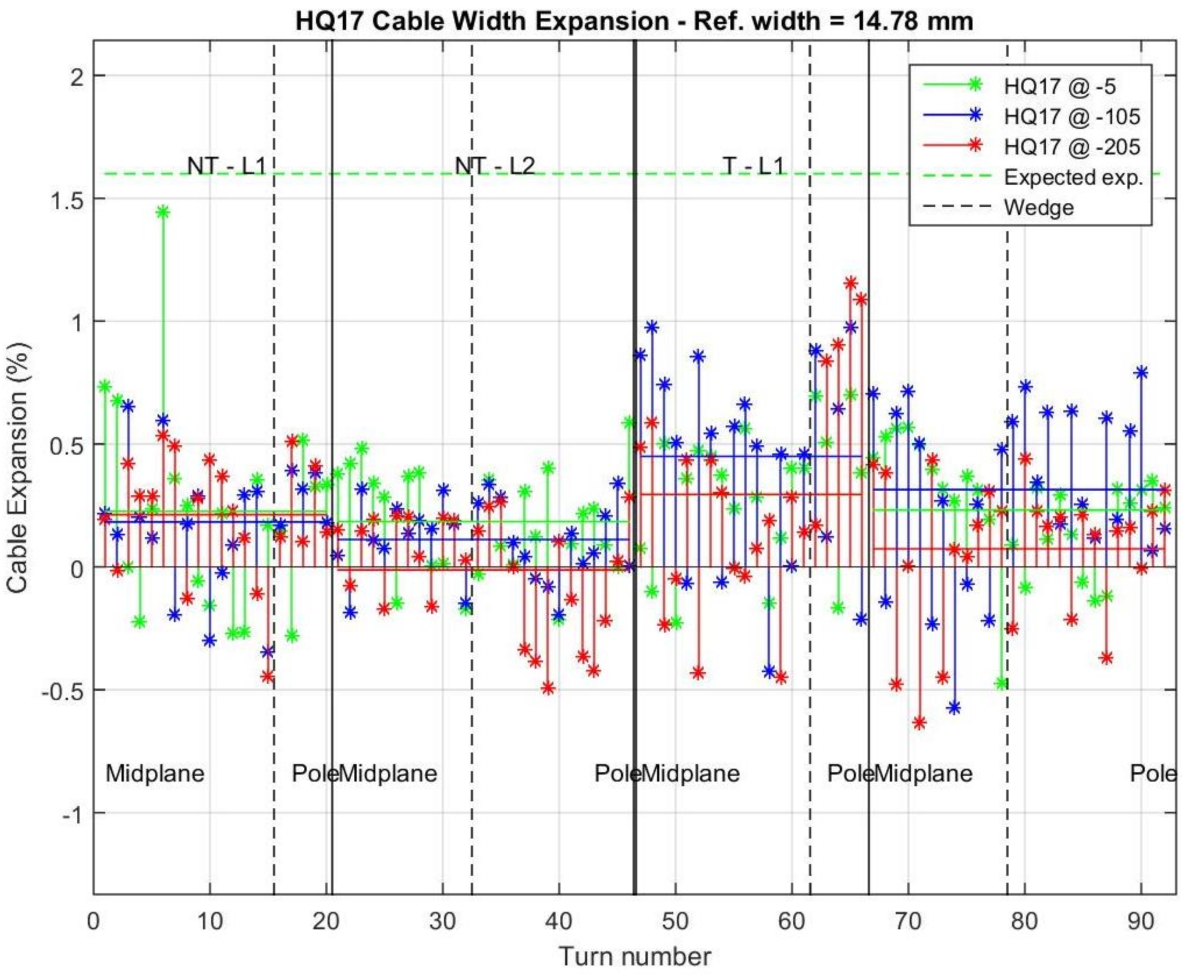
- Turn locations
- Turns radial/azimuthal shift
- Cables width and thickness
- Cables contraction and expansion

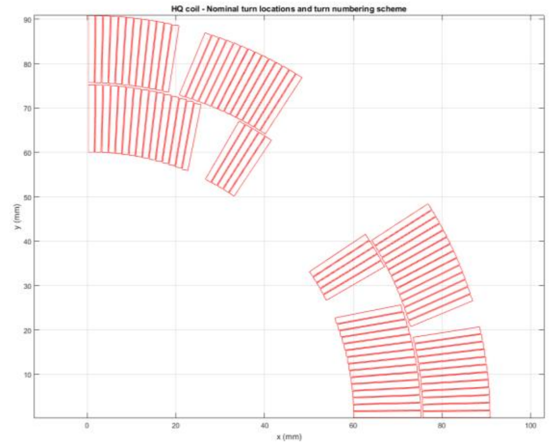






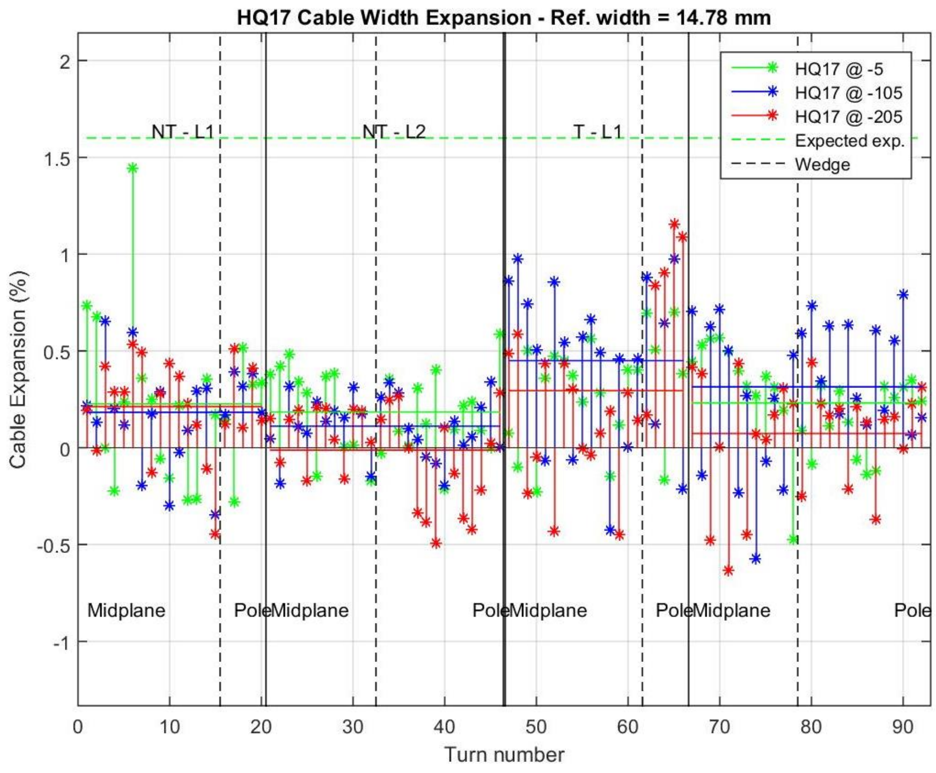
Example plot

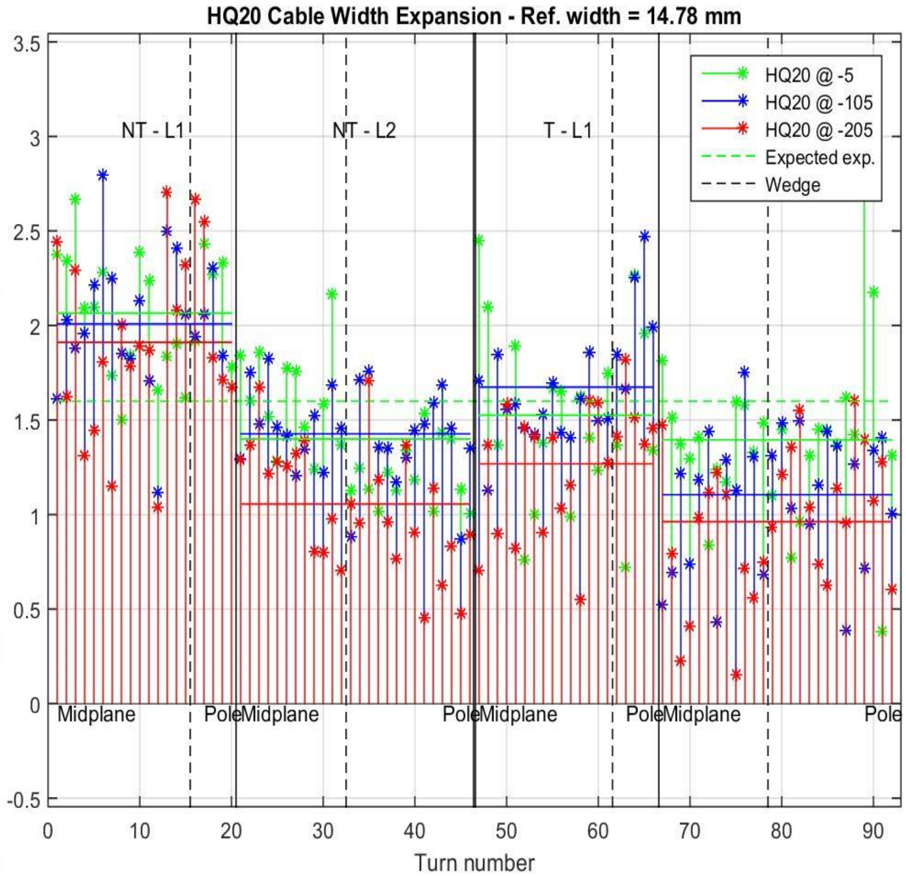




HQ17-20 Comparison – Cable width

- Different cable insulation
- Expected same expansion



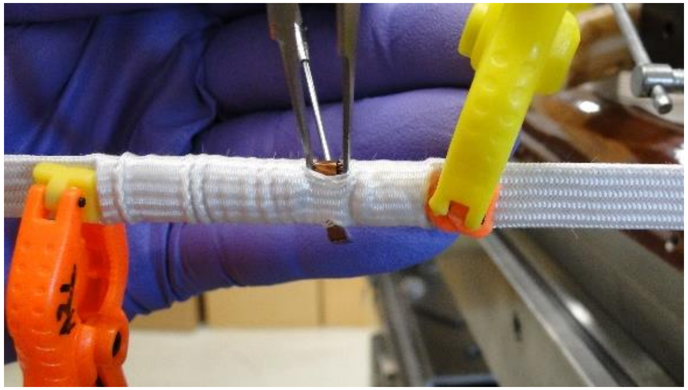


- Insulation affects expansion

Cable insulation – HQ17 vs HQ20

HQ17 - Braided on insulation

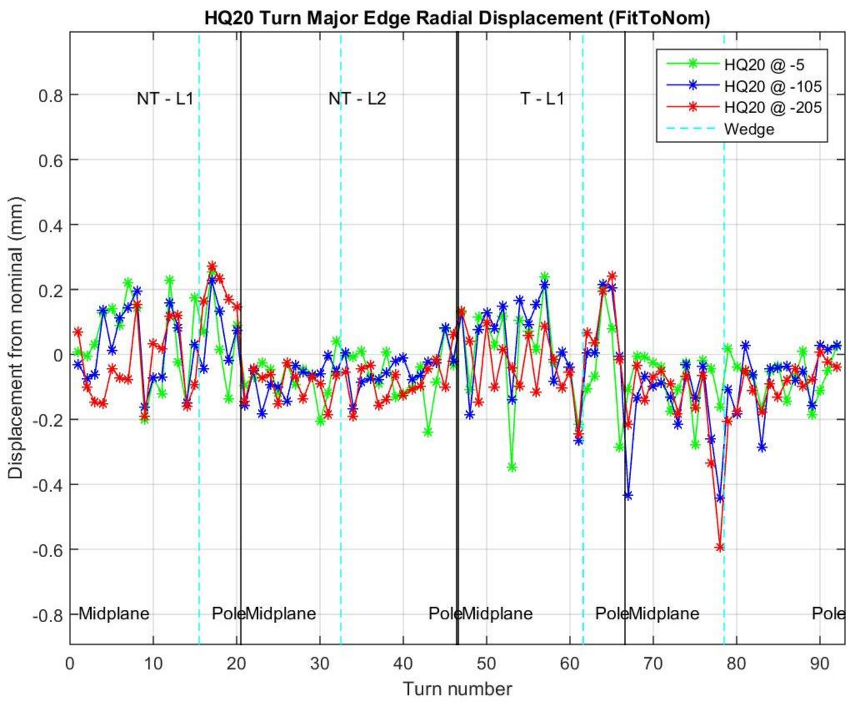
- Cable more constricted
- Less expansion/variance

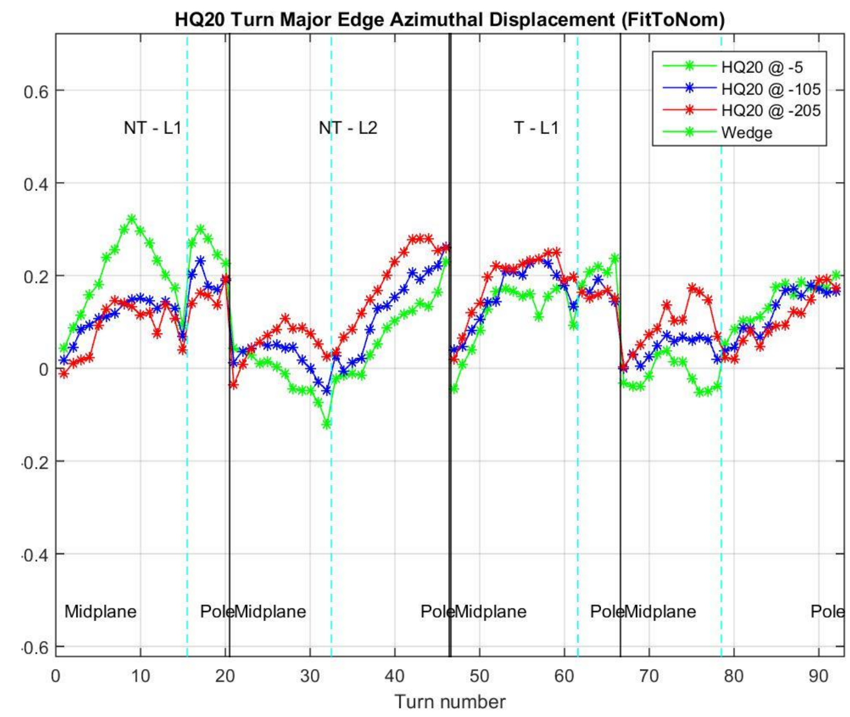


HQ17 - Sock insulation

- Cable more constricted
- Much more expansion/variance

RADIAL VS AZIMUTHAL TURN DISPLACEMENT



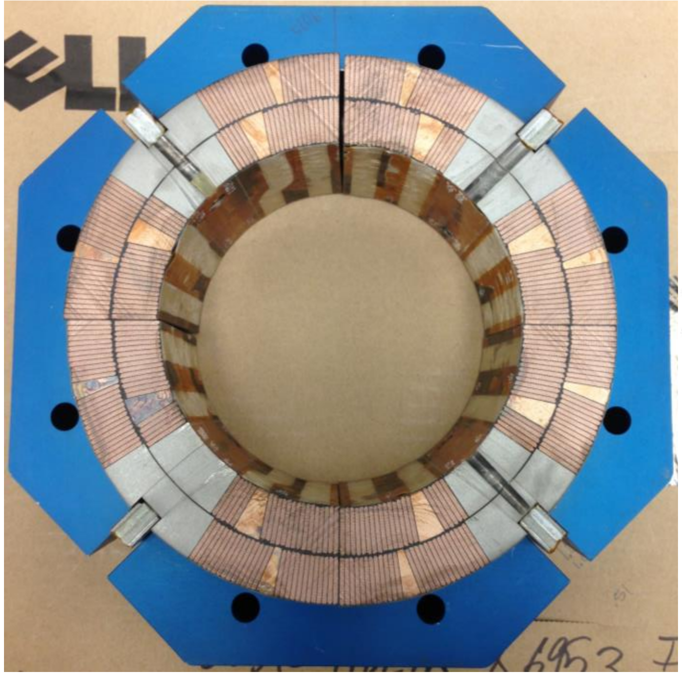


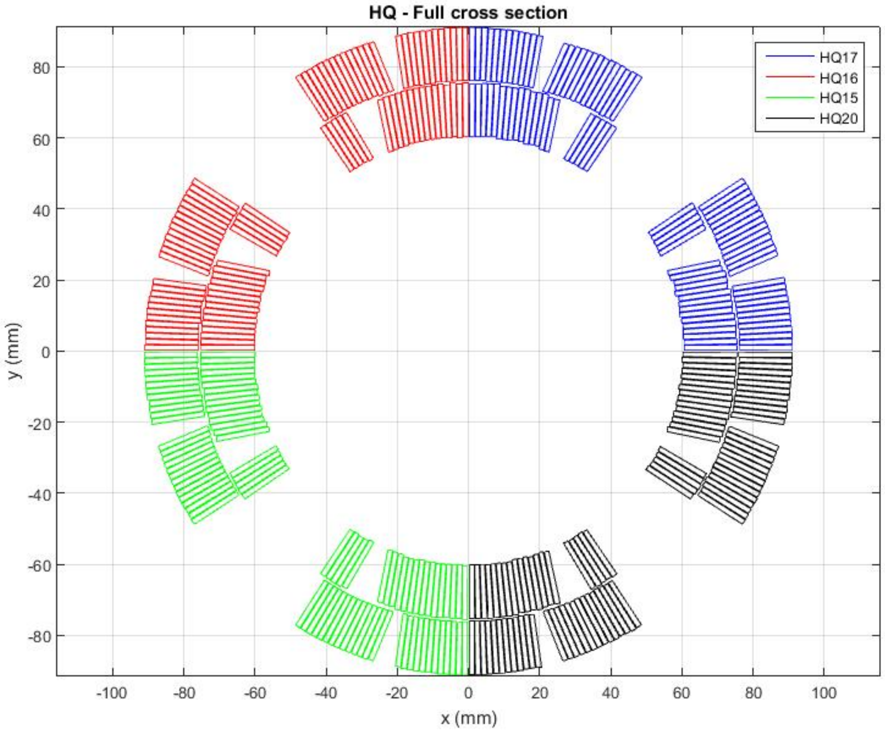
- Radial displacement fast varying
- Azimuthal continuous: the turns push one another
- Turns shift up to 300µm over the span of 200mm
- Wedge push turns azimuthally
- Determine trends and verify outlier

AZIMUTHAL DISP. POSITIVE FROM MIDPLANE TO POLE

Full cross section measurement

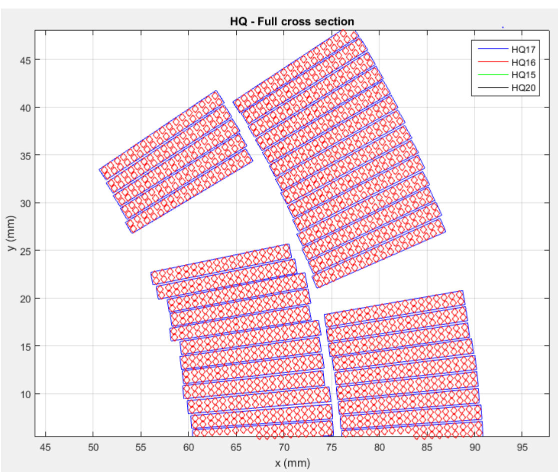
Assemble 4 coil segment to obtain a full cross section → Measure turn location on the full cross section

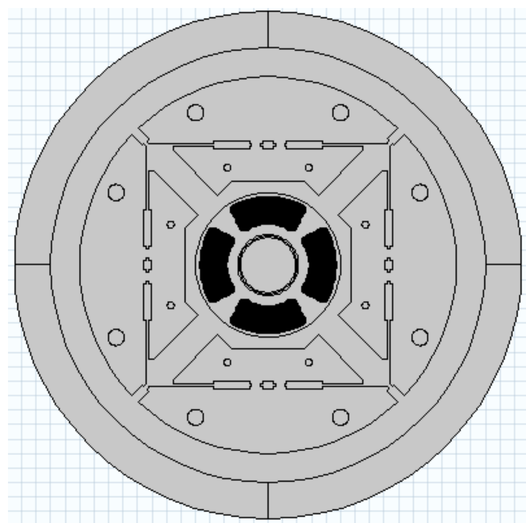


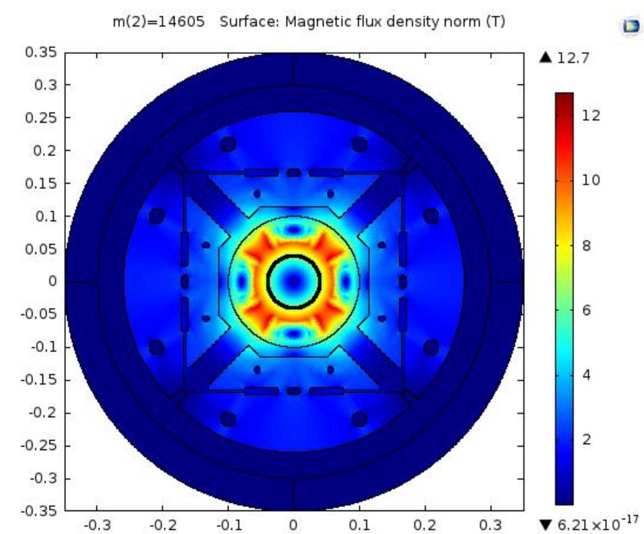


Impact on field quality

Compute position of each current → Input in a magnet simulation model → Compute field and multipoles







Future work

MATCHING NUMERICAL RESULTS WITH EXPERIMENTAL DATA REQUIRES FURTHER EFFORTS !!!

Cancel out first order harmonics (simulating probe positioning)

Compensate for collars deformation due to assembly

Quantify the effect of strand pattern inside each turn on multipoles

Quantify the effect of turn corner measurement error on multipoles

Conclusions

Data on cable expansion gave useful information to choose a braided on cable insulation wrt the sock

Hypotheses about turn variance along the magnet axis have to be revised

Magnetic measurement and numerical results don’t match (at this stage)…at least needed further manipulations

Turn variance is too high to compare a single cross section to the 10cm average of the rotating coils measurement


WHAT'S NEXT?