Program I.D. number: MT25-Tue-Af-Po2.03-06

Current Center Line Measurement of ITER TF Coil

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Background

In order to confirm TF coil's functionality, accurate measurement of current center line (CCL) for winding pack (WP) inside TF coil is necessary. Direct geometrical determination of CCL positon is impossible due to complex structure of WP, while magnetic determination involves complicated inverse problem of Biot-Savart equation. There was a strong need for more simple yet accurate method to determine CCL positions of WP.

Objectives

- ❖ To develop a method which can determine CCL positions of WP with 1 mm accuracy in factory environment.
- ❖ To apply the developed method to determine CCL positions of actual WP for ITER TF coil.

Conclusion

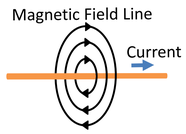
- ❖ A method to determine CCL positions of WP with composition of magnetic field measurements and geometrical measurements has been developed. Conductor positions of DPs at each cross section can be determined magnetically with 0.73 mm accuracy and therefore the CCL positions of DPs with 0.73 mm accuracy. Then with geometrical measurements of DP positions and insulation thicknesses within WP, CCL positions of WP can be determined with 0.83 mm accuracy.
- ❖ CCL positions of WP for ITER TF Coil #13 have been calculated. At one tight tolerance cross section, result deviates 1.49 mm from nominal values; however, at other cross sections, CCL position results satisfied tolerance criteria defined for WP CCL for ITER TF coil.

Hypothesis

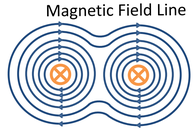
Relationships between Magnetic Field Curves and Conductor Positions

Magnetic Field Lines

By a Line Source

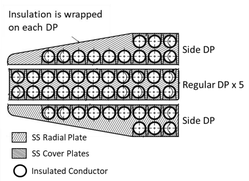


By Two Line Sources

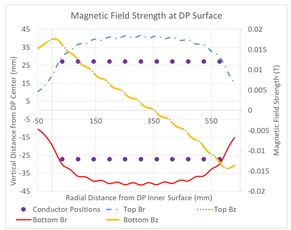


When there are multiple discrete line sources, the resultant magnetic field is a composition of the magnetic fields generated by individual line sources.

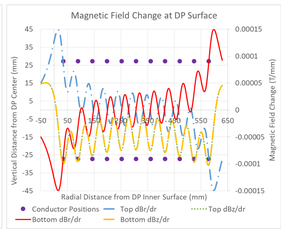
WP for TF coil



- WP is a coil with discrete turns.
- The ripples induced by individual turns can only be seen at close range.



- On DP, all the turns are accessible for close range measurements.
- The ripples correspond to conductor turn positions.

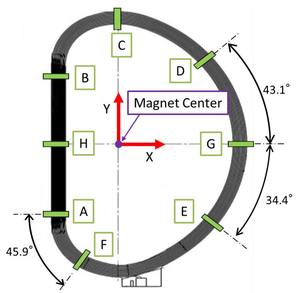


Shapes of ripple is relatively easier to evaluate for derivatives of magnetic field components.

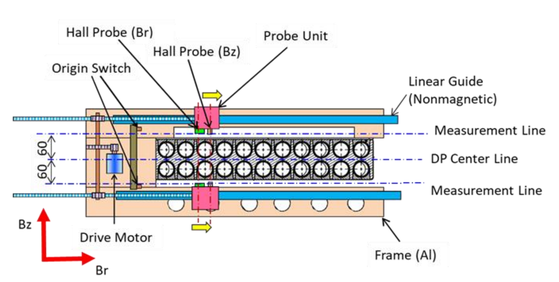
Magnetic Measurements

Instrument Design and Measurement Setup

Measurement Cross Sections



Magnetic Field Measurement Instrument



Instrument Design

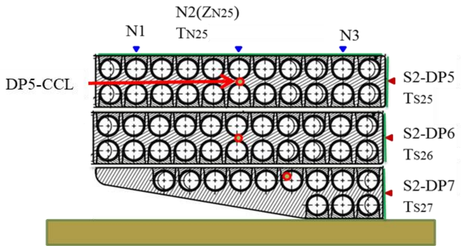
- Hall probes as magnetic field sensors
- Temperature of Hall probes are kept @ 40° C
- Sensor units are installed on top and bottom to measure both sides simultaneously

Measurement Setup

- 8 cross sections, A-H
- DP is powered up with 1kA current
- 1360 sets of magnetic measurement data per cross section
- 30 mins duration per cross section

Geometrical Measurements

Measurements on DPs after Stacking



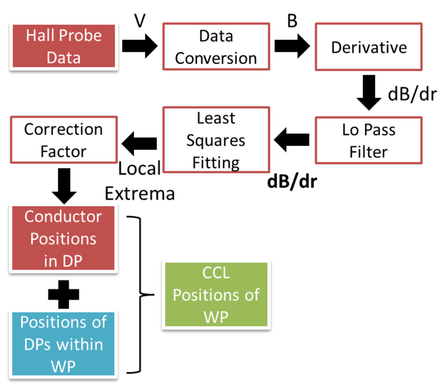
- At each cross sections, positions of DPs are measured with laser tracker. Coordinate system for the measurements is with respect to the magnet center.
- Insulation thickness are measured with Eddy current probe.

Measurement Parameters

- Inner Surface Coordinates: X_{S2i}, Y_{S2i}, Z_{S2i}
- Inner Surface Insulation Thickness: T_{S2i}
- Upper Surface Parameters: $N_1(Z_{2i})$, $N_2(Z_{2i})$, $N_3(Z_{2i})$
- Upper Surface Insulation Thickness: T_{N2i}

Data Analysis

Analysis Method



CCL is defined as a geometrical barycenter line of all the conductor turns within a coil.

Error Analysis

Summary of Error Sources

Process	Error Source	Error in CCL
Magnetic Measurement	Noise in Hall probe measurements, 0.035 mV	0.25 mm
Instrument Setup	Upper insulation thickness variation, 1.0 mm maximum	0.2 mm
Drive Unit Controller	0.05 mm	0.05 mm
Temperature Variation of DP	4 °C max variation Temp. Correction to 20 °C	0.03 mm
Magnetic Data Analysis	±0.2 mm	0.2 mm
Geometrical Measurement	Laser tracker accuracy with T-probe, 0.1 mm	0.1 mm
Total Maximum Error		0.83 mm

This is the **maximum error** assuming errors occurs in the same direction. In reality, some errors takes positive values while others negative; those errors cancel out each other and resultant total error would be much smaller.

Results

CCL of WP for ITER TF Coil #13

Summary of CCL Position Results

Cross Section	Nominal Values		Composite Method			Geometrical Estimation			Criteria
			Results		Deviation	Results		Deviation	
	X	Y	X	Y	r	X	Y	r	r
A	-2620.7	-3700.0	-2621.5	-3699.9	0.83	-2620.2	-3700	-0.50	± 1.0
B	-2620.7	3700.0	-2621.5	3700.1	0.82	-2620.1	3700	-0.62	± 1.0
C	0	6296.4	0.00853	6297.2	0.75	0	6296.2	-0.23	± 1.0
D	3646.0	4437.0	3646.7	4437.7	0.99	3645.0	4436.1	-1.34	± 2.0
E	4253.2	-3695.0	4253.0	-3695.1	-0.07	4252.0	-36954.2	-1.49	± 2.0
F	-1934.7	-5598.0	-1935.7	-5599.1	1.49	-1934.9	-5598.2	0.31	± 1.0
G	5398.6	0	5399.5	-0.1	0.88	5398.0	0	-0.64	± 2.0
H	-2620.7	0	-2620.8	-0.288	0.12	-2619.9	0	-0.78	± 1.0

All the parameters are in mm and at room temperature.
r: radial coordinate; positive indicates outward.

- Nominal values: Target design values common for all the TF coils.
- Composite method results: Results from the method presented here.
- Geometrical estimation is calculated from geometrical measurement data through production.
- Deviation shows the difference from nominal value.
- Criteria: Tolerance criteria for ITER TF coils.

- All of CCL positions satisfied the tolerance except at Cross Section F, which locates between straight region and large curvature region.
- At straight part, criteria is set ±1.0 mm; it is acceptable because there is no space left in conductor grooves in that region.
- At large curvature part, criteria is set ±2.0 mm; it is reasonable considering there are ±1.3 mm spaces in grooves for conductor turns to adjust for DP deformations which might happen during production, i.e. welding and epoxy heat curing..
- At small curvature regions between straight region and large curvature region, criteria is set ±1.0 mm even though there are ±1.8 mm spaces left in conductor grooves. Since conductor turn positions cannot be adjusted at straight part, as consequence, some deviations are expected at small curvature regions.
- Geometrical measurement cannot detect the effect of DP deformations on conductor turn positions after some operations because conductor turn positions cannot be confirmed visually.

Presented at Magnet Technology Conference , 29 August 2017, Amsterdam, Netherland; Session: Superconducting Magnets for Fusion; Program I.D. number: MT25-Tue-Af-Po2.03-06