Inspections on larger coil size of 7-m long practice coil for D1

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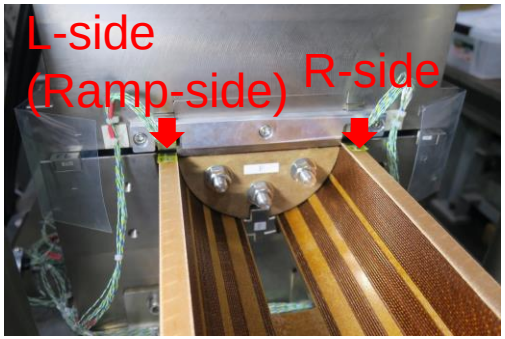
KEK

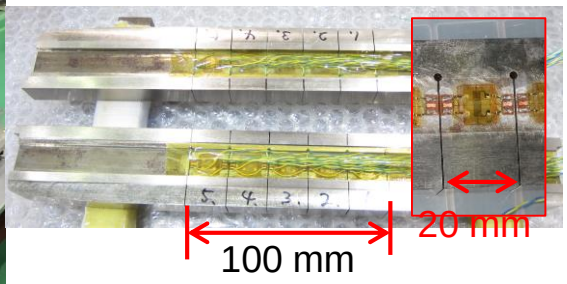
On behalf of CERN-KEK Collaboration for D1 Development for HL-LHC

Outline

- Coil size of 7 m-long practice coil
- Results of inspections
  - Wedge size
  - Visual inspection of cables
  - Bare cable thickness
  - Insulation tape thickness
  - 10 stack measurement

Coil size measurement of D1

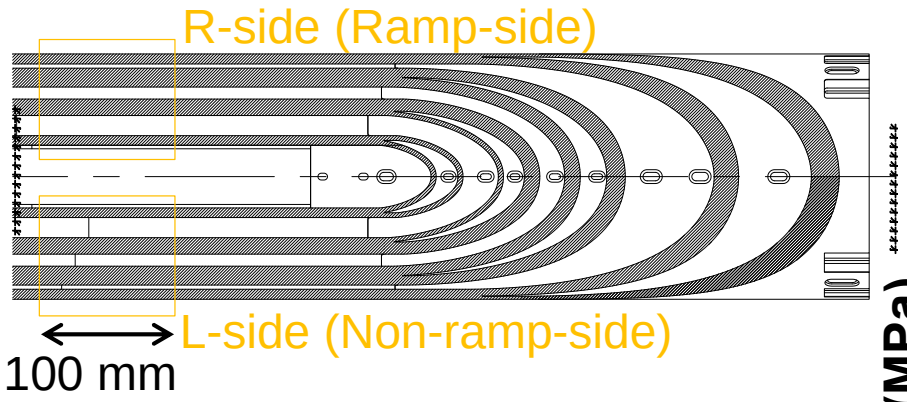




Pushing bars

- 7 m-long practice coil (Coil LP-0) was cured in May, 2020 in Hitachi.
- Coil size measurement was performed at Hitachi using the equipment prepared by KEK.
- Coil size was evaluated for a quadrant coil (R-side, L-side).
- Every 20 mm-long section was measured by using pushing bars instrumented by strain gauges. 100 mm-long section can be measured at the same time.
- Coil size in the straight section of LP-0 was compared with those of 2 m-long coils fabricated by KEK during model magnet development.

Coil size of LP-0 and 2 m-long coils

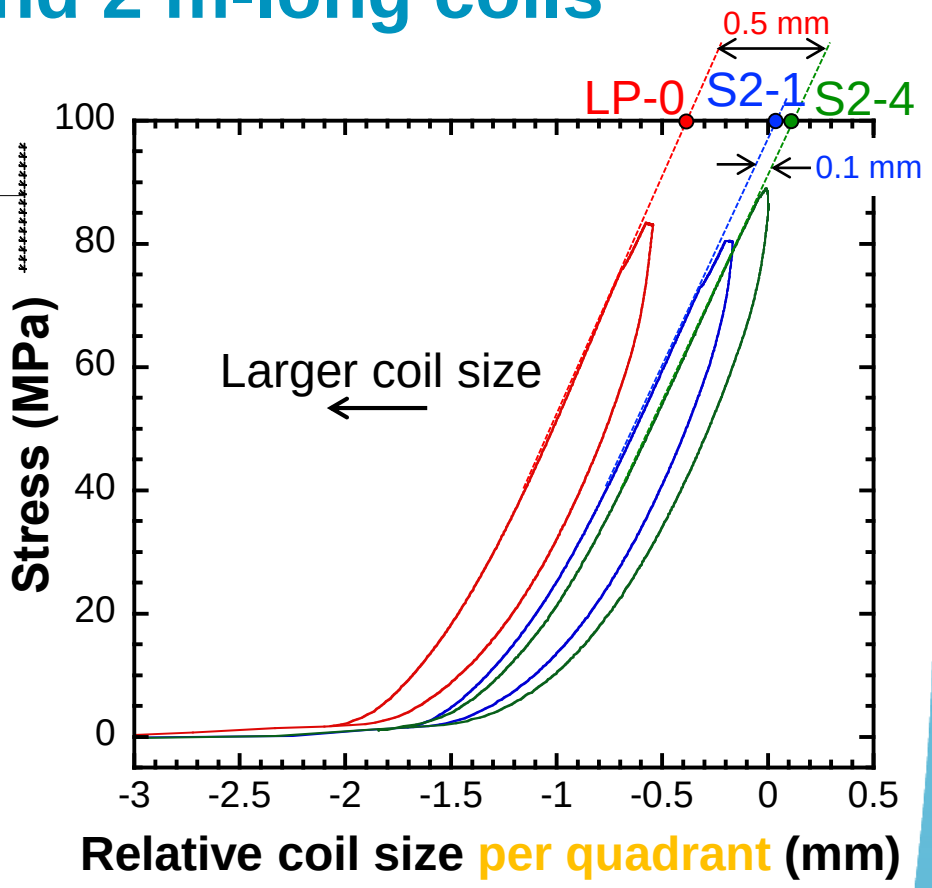


With respect to coil S2-4

LP-0 is 0.5 mm larger

S2-1 is 0.1 mm larger

per quadrant coil



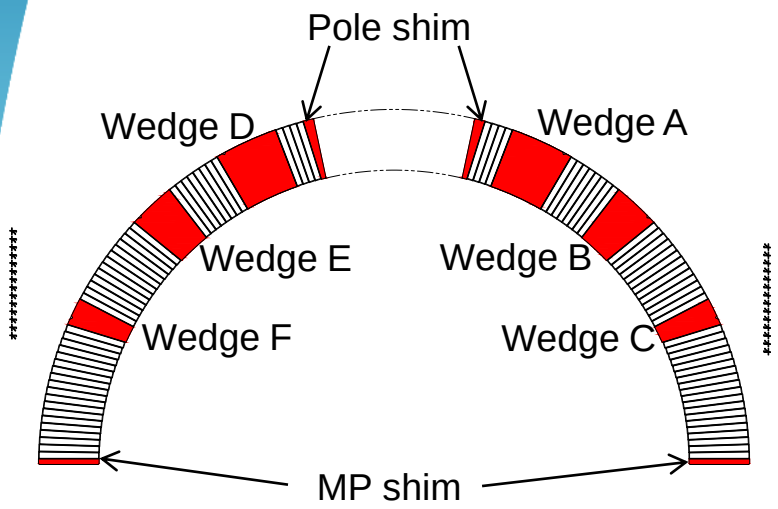
Scatter of coil size over SS in LP-0 = ±0.05 mm

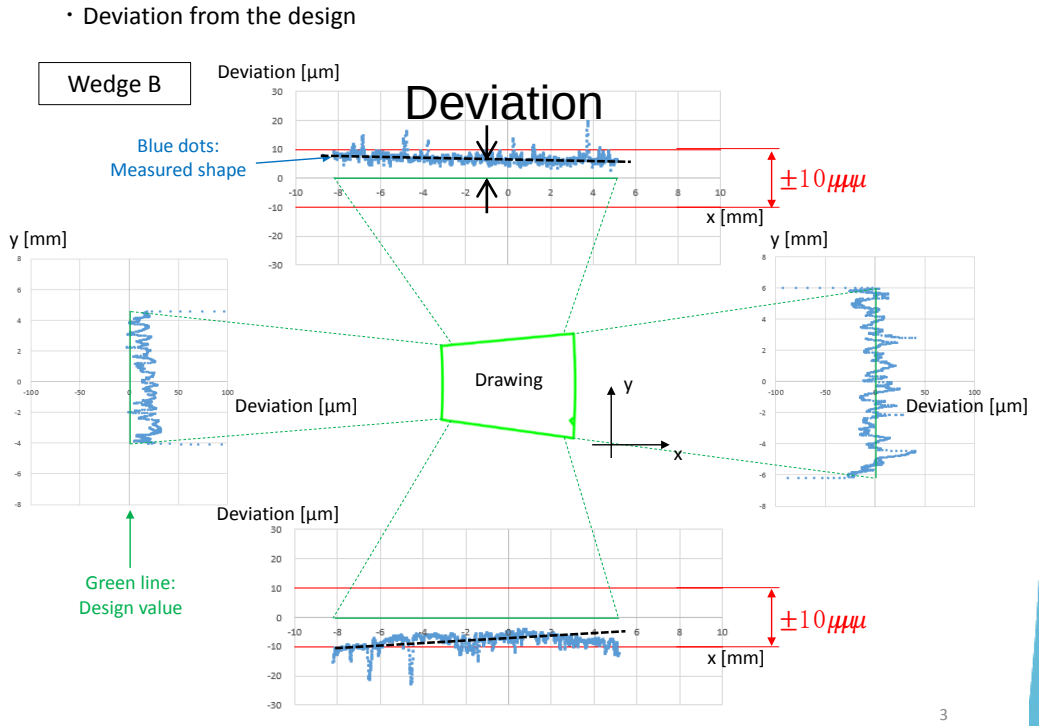
Coil ID	Length	Remarks	Measurer	Relative coil size at 100 MPa wrt S2-4	
				L-side	R-side
LP-0	7 m	Practice coil	Hitachi	+0.48	+0.51
S2-1	2 m	Same design as MBXFS2 coil Not used for magnet assembly due to cable detachment	Hitachi	+0.07	+0.09
S2-4	2 m	Assembled into MBXFS3	KEK	–	–

Possible reasons of larger coil size

- Wedge size → Checking measured wedge size
- Cable
  - Insulation wrapping → Visual inspection
  - Bare cable thickness → Document check
  - Insulation tape thickness → Measured in this campaign
  - 10 stack measurement → Measured in this campaign

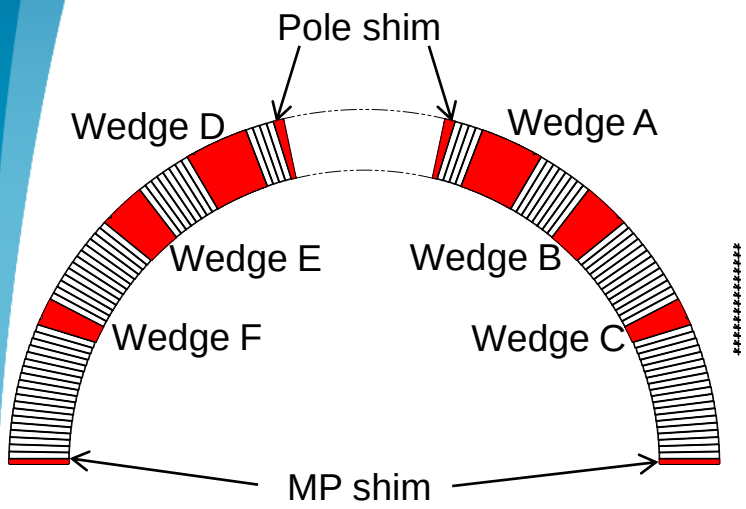
Inspection of wedge size





- All wedges used for S2-4 and LP-0 have been measured by CMM or optical method.
- Deviation from the design size in the azimuthal direction of each wedge was evaluated and summed up per quadrant coil.

Difference of azimuthal wedge size



Deviation of the azimuthal wedge size (μm)

Coil ID	LP-0		S2-4	
	L-side	R-side	L-side	R-side
Pole shim	+16.6	+15.5	+6.3	+18.8
Wedge A or D	+11.2, +3.6	+11.7	+11.8	+8.9
Wedge B or E	+27, +5	+1.5	-8.4	-22.7
Wedge C or F	+31, +9.3	+17.7	-7.8	-15.8
MP shim	-11.3	-8	-6.3	-8.3
Total (average)	45.3	38.4	-4.4	-19.1

- Measured size error wrt the design thickness per quadrant coil
  - LP-0: L-side = +38 μm, R-side = +45 μm
  - S2-4: L-side = -4 μm, R-side = -19 μm

  } LP-0 > S2-4 by 0.04 – 0.06 mm
- Total wedge size of LP-0 is 60 μm larger by design than that of S2-4

- Total wedge size of LP-0 is 0.10 – 0.12 mm larger than that of S2-4

Cable ID

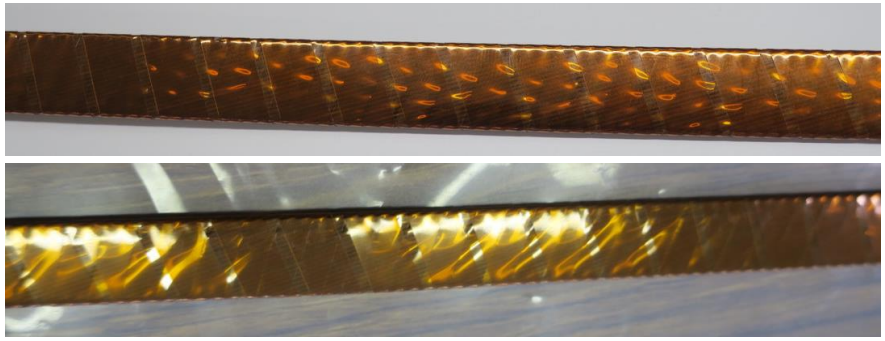
Coil ID	Bare cable	Insulated cable	Coils wound using the same cable (Magnet ID)
Coil LP-0	02B50866B	HCMB_AI473T50866B	–
Coil S2-1	02G00346A	HCMB-AO47CM001622	S1-1, S1-2 (MBXFS1)
Coil S2-4	02B81232A	HCMB_AI47CR001623	Coil S2-5 (MBXFS3)

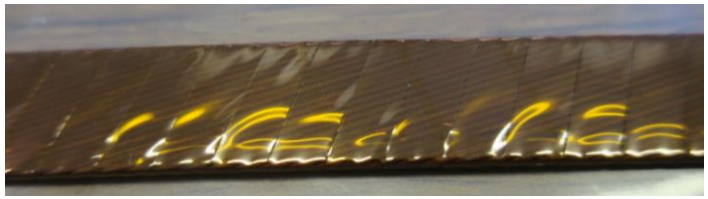
Visual inspection

with 1st, 2nd and 3rd insulations

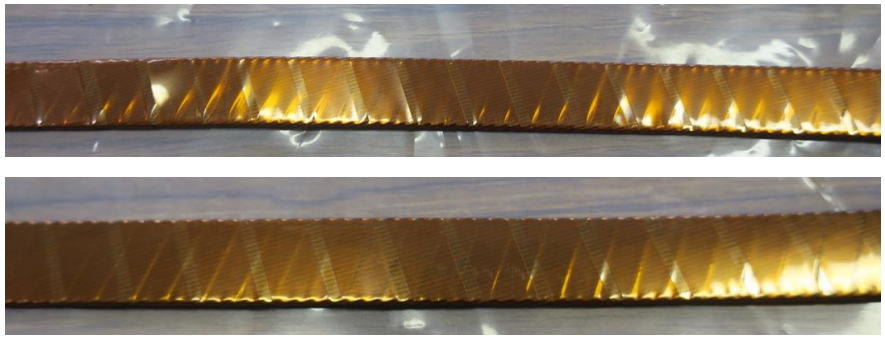
after removing 3rd layer

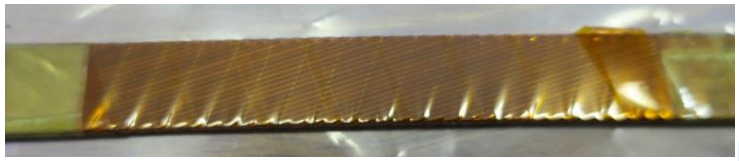
LP-0



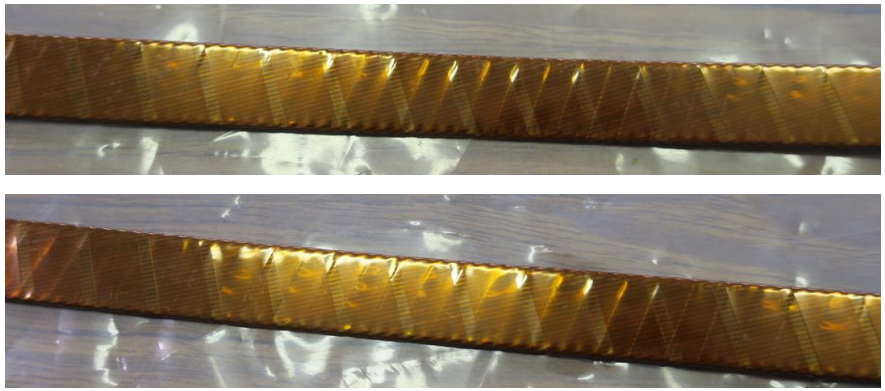


S2-1





S2-4



- Insulation tapes of LP-0 cable seems to be loosely wound.

Bare cable thickness

Coil LP-0

02B50866B (HCMB_AI47-3T50866B)

NbTi Rutherford Cable Production Report
LHC Type 02 cable 02B50866B

Authors: J. Fleiter, A. Bonasia, and A. Ballarino

A unit length of LHC Type-02 series cable (cable ID: 02B50866B) fabricated by Alstom and delivered to CERN in Apr. 2006 was approved on the 29th May 2006 as compliant to the technical specification EDMS 90274 (IT-2471). This document reports on the results of the tests carried out as part of the quality assurance plan of Rutherford cable production. The measured residual twist of the cable and the inter-strand contact resistance are not reported in this document.

TABLE 1: RESULTS OF QUALITY CONTROL TESTS performed on cable 02B50866B

PRODUCTION INFO			
Cable Identification:	02B50866B		
Manufacturer	Alstom		
Cabling run ID	2R206		
Date of Delivery to CERN	Apr-2006		
CABLE DIMENSIONS			
	average	**(σ)**	**Specification**
Cable length (m)	**745**	n.a.	≥750
Cable mid thickness @ 50 MPa (mm)	**1.481**	(0.002)	1.480 ±0.006
Cable width (mm)	**15.090**	(0.003)	15.10 +0, -0.02
Cable Keystone (deg)	**0.89**	(0.004)	0.90 ±0.05
Cable Transposition Pitch (mm)	**101**	n.a.	100 ±5
Cable Transposition Pitch direction (-)	**LEFT**		LEFT
Acid test	**PASSED**		PASSED
Bend test	**PASSED**		PASSED
Edge test	**PASSED**		PASSED
CABLE ELECTRICAL PERFORMANCES			
	average		**Specification**
I_c of extracted strands at **1.9 K** and **9 T**	**408**		>360
RRR extracted strands	**230**		>70
CABLE UL APPROVAL			
Cable UL approval according to specification EDMS 90274	**APPROVED 29 May 2006**		

Coil S2-1

02G00346A (HCMB-AO47-CM001622)

NbTi Rutherford Cable Production Report
LHC Type 02 cable 02G00346A

Authors: J. Fleiter, A. Bonasia, and A. Ballarino

A unit length of LHC Type-02 series cable (cable ID: 02G00346A) fabricated by IGC and delivered to CERN in Aug. 2004 was approved on the 27th August 2004 as compliant to the technical specification EDMS 90274 (IT-2471). This document reports on the results of the tests carried out as part of the quality assurance plan of Rutherford cable production. The measured residual twist of the cable and the inter-strand contact resistance are not reported in this document.

TABLE 1: RESULTS OF QUALITY CONTROL TESTS performed on cable 02G00346A

PRODUCTION INFO			
Cable Identification:	02G00346A		
Manufacturer	IGC		
Cabling run ID	00206		
Date of Delivery to CERN	Aug-2004		
CABLE DIMENSIONS			
	average	**(σ)**	**Specification**
Cable length (m)	**749**	n.a.	≥750
Cable mid thickness @ 50 MPa (mm)	**1.481**	(0.001)	1.480 ±0.006
Cable width (mm)	**15.087**	(0.002)	15.10 +0, -0.02
Cable Keystone (deg)	**0.88**	(0.007)	0.90 ±0.05
Cable Transposition Pitch (mm)	**101**	n.a.	100 ±5
Cable Transposition Pitch direction (-)	**LEFT**		LEFT
Acid test	**PASSED**		PASSED
Bend test	**PASSED**		PASSED
Edge test	**PASSED**		PASSED
CABLE ELECTRICAL PERFORMANCES			
	average		**Specification**
I_c of extracted strands at **4.2 K** and **6 T**	**414**		>368
RRR extracted strands	**Not measured**		>70
CABLE UL APPROVAL			
Cable UL approval according to specification EDMS 90274	**APPROVED 27 August 2004**		

Coil S2-4

02B81232A (HCMB_AI47-CR001623)

NbTi Rutherford Cable Production Report
LHC Type 02 cable 02B81232A

Authors: J. Fleiter, A. Bonasia, and A. Ballarino

A unit length of LHC Type-02 series cable (cable ID: 02B81232A) fabricated by Alstom and delivered to CERN in Jan 2005 was approved on the 8 Apr. 2005 as compliant to the technical specification EDMS 90274 (IT-2471). This document reports on the results of the tests carried out as part of the quality assurance plan of Rutherford cable production. The measured residual twist of the cable and the inter-strand contact resistance are not reported in this document.

TABLE 1: RESULTS OF QUALITY CONTROL TESTS performed on cable 02B81232A

PRODUCTION INFO			
Cable Identification:	02B81232A		
Manufacturer	Alstom		
Cabling run ID	08123		
Date of Delivery to CERN	Jan-2005		
CABLE DIMENSIONS			
	average	**(σ)**	**Specification**
Cable length (m)	**753**	n.a.	≥750
Cable mid thickness @ 50 MPa (mm)	**1.478**	(0.002)	1.480 ±0.006
Cable width (mm)	**15.092**	(0.002)	15.10 +0, -0.02
Cable Keystone (deg)	**0.91**	(0.01)	0.90 ±0.05
Cable Transposition Pitch (mm)	**101**	n.a.	100 ±5
Cable Transposition Pitch direction (-)	**LEFT**		LEFT
Acid test	**PASSED**		PASSED
Bend test	**PASSED**		PASSED
Edge test	**PASSED**		PASSED
CABLE ELECTRICAL PERFORMANCES			
	average (measurements)		**Specification**
I_c of extracted strands at 1.9 K and 9 T	**401**		>360
RRR extracted strands	**181**		>70
CABLE UL APPROVAL			
Cable UL approval according to specification EDMS 90274	**APPROVED 8 Apr. 2005**		

- No difference in bare cable thickness between Coil S2-1 and LP-0 cables.
- 3 μm thinner in S2-4 cable → 0.13 mm thinner for 44 turns

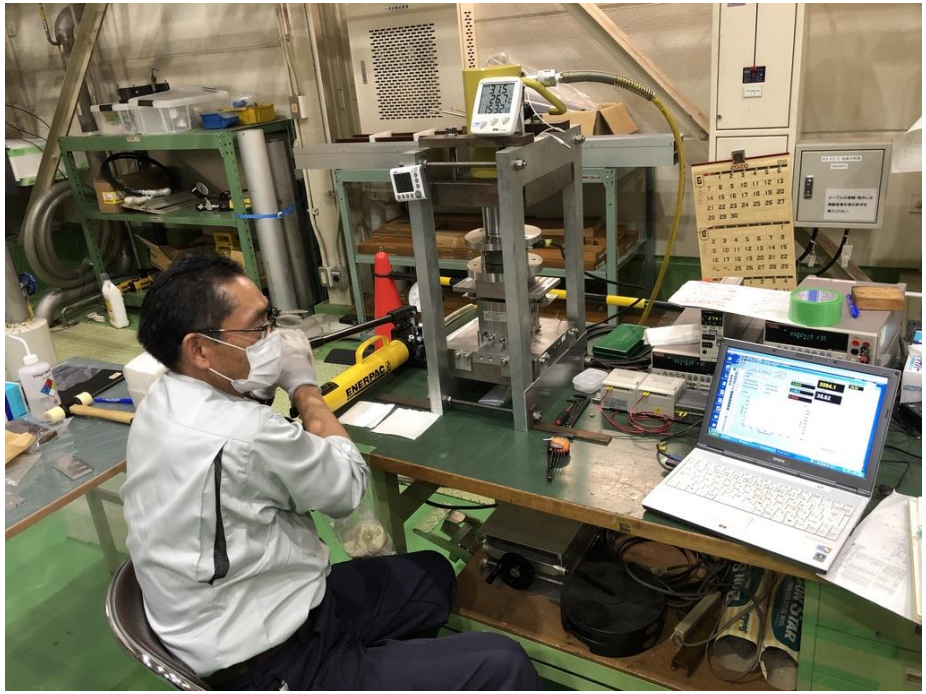
Insulation tape thickness

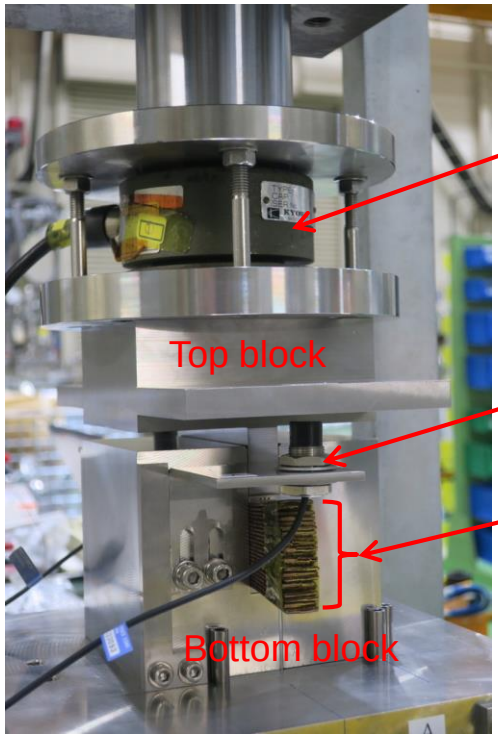
Thickness of insulation tapes unwrapped from each cable was measured using a micrometer.

Coil ID	Cable ID Bare cable Insulated cable	Layer of insulation	#1	#2	#3	#4	#5	Ave.
Coil LP-0	02B50866B HCMB_AI47-3T50866B	1st	0.051	0.051	0.051	0.050	0.050	0.051
		2nd	0.051	0.051	0.050	0.051	0.049	0.050
		3rd	0.067	0.067	0.067	0.067	0.066	0.067
Coil S2-1	02G00346A HCMB-AO47-CM001622	1st	0.050	0.051	0.049	0.050	0.049	0.050
		2nd	0.049	0.051	0.051	0.052	0.051	0.051
		3rd	0.066	0.067	0.067	0.067	0.066	0.067
Coil S2-4	02B81232A HCMB_AI47-CR001623	1st	0.051	0.051	0.051	0.051	0.051	0.051
		2nd	0.051	0.051	0.051	0.051	0.051	0.051
		3rd	0.069	0.068	0.068	0.068	0.068	0.068

No difference in insulation tape thickness

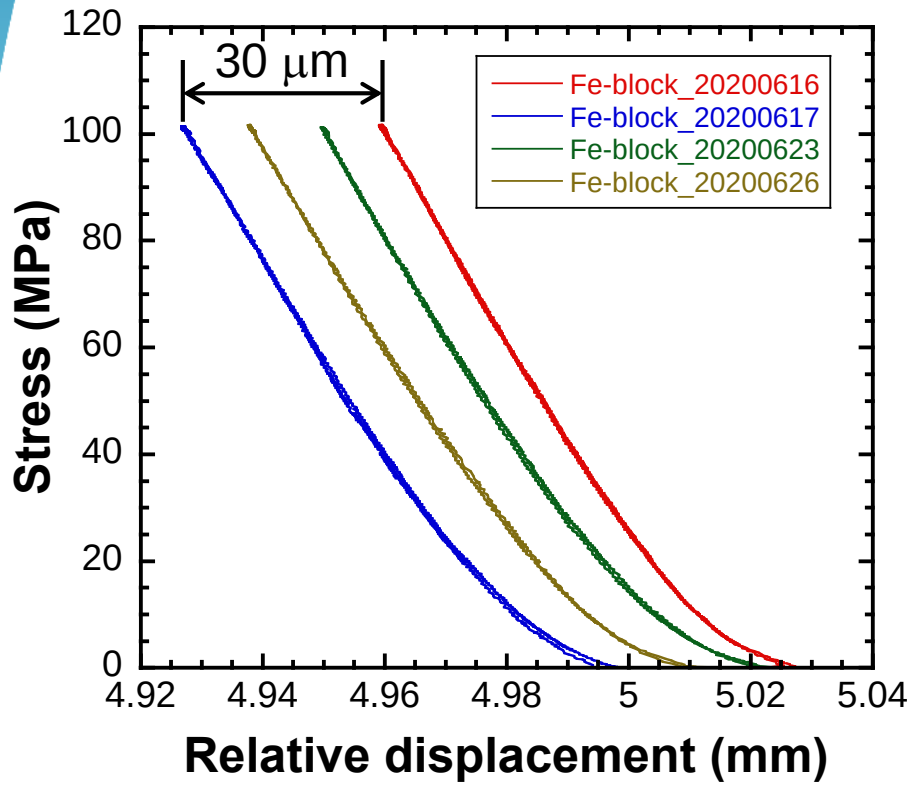
10 stack measurement

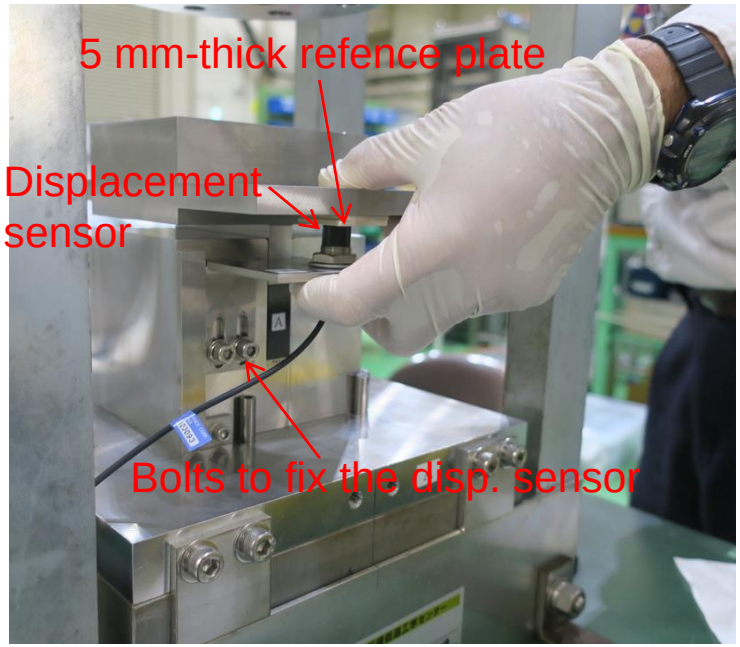




- Measurement setup: 50 ton hydraulic press, manual pump, 20 ton load cell, eddy current displacement sensor
- Curing
  - 22 cable stack (a half number of turns of D1 coil) was cured at 190^{o}C for 0.5 h with the pressure of 50 MPa.
- Compressive test
  - Reference specimen(SS400 block), cable stack
  - Loading and unloading up to 100 MPa
  - Measured data of the second cycle among three cycles were used.

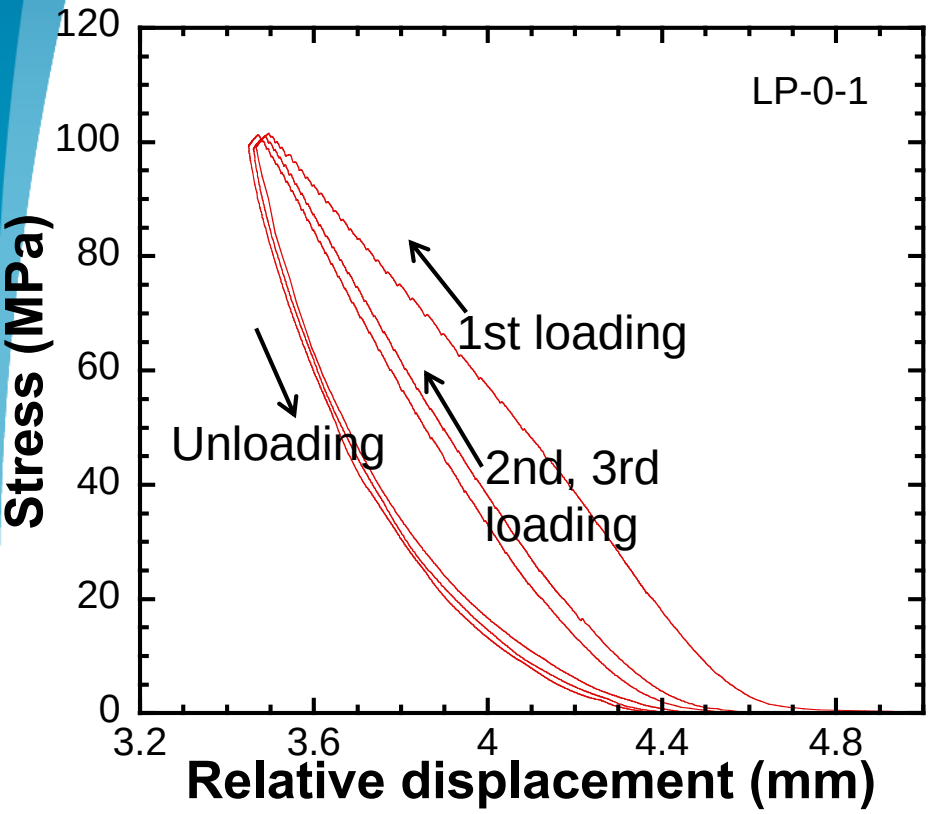
Measured stress-displacement curve of Fe block (only 2nd loading/unloading curve, raw data)

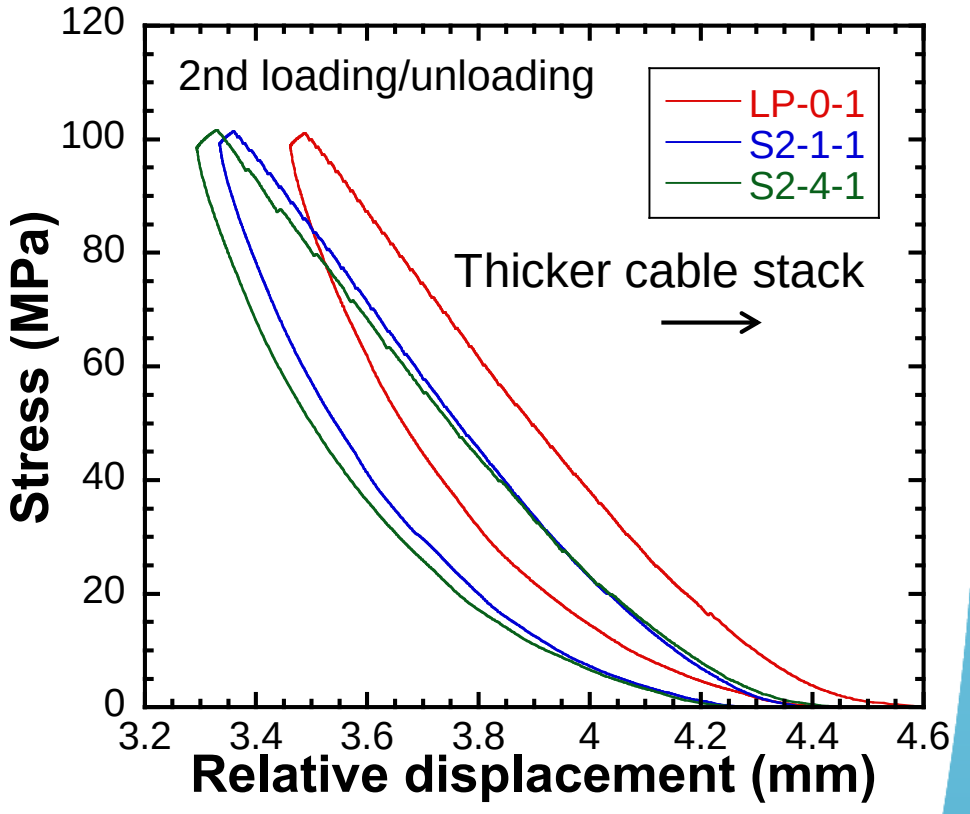




- Offset of 30 μm at maximum among the measured Fe-block data was found. This comes from mispositioning of the displacement sensors.
- This offset was corrected during data analysis.
- Measured data of Fe block were used to subtract deformation of the measuring jig.

Measured stress-displacement curve of cable stack (raw data)





- The curves of the 2nd and 3rd run are more reproducible, while the 1st run exhibits larger hysteresis.

  → 2nd loading curve was used for the following analysis

Data analysis: Deformation of cable stack

Cable stack thickness was compared at 100 MPa

Cable stack thickness at the stress of σ ($y_c(\sigma)$)
= Initial thickness ($y_{0,c}$) + Deformation of cable stack ($\Delta y_c(\sigma)$)

Deformation of cable stack ($\Delta y_c(\sigma)$) was derived as follows.

Cable stack $\Delta y_c^m = \Delta y_c + \Delta y_{jig}$

Fe block $\Delta y_{Fe}^m = \Delta y_{Fe} + \Delta y_{jig}$

Hooke's law $\Delta y_{Fe} = \frac{\sigma}{E} y_{0,Fe}$

Δy_c^m : Measured cable deformation including deformation of jig
Δy_{jig} : Deformation of jig
Δy_{Fe}^m : Measured deformation of Fe block including deformation of jig
Δy_{Fe} : Deformation of Fe block
E : Young's modulus of SS400 (206 GPa)
$y_{0,Fe}$: Initial thickness of Fe block (40.017 mm)

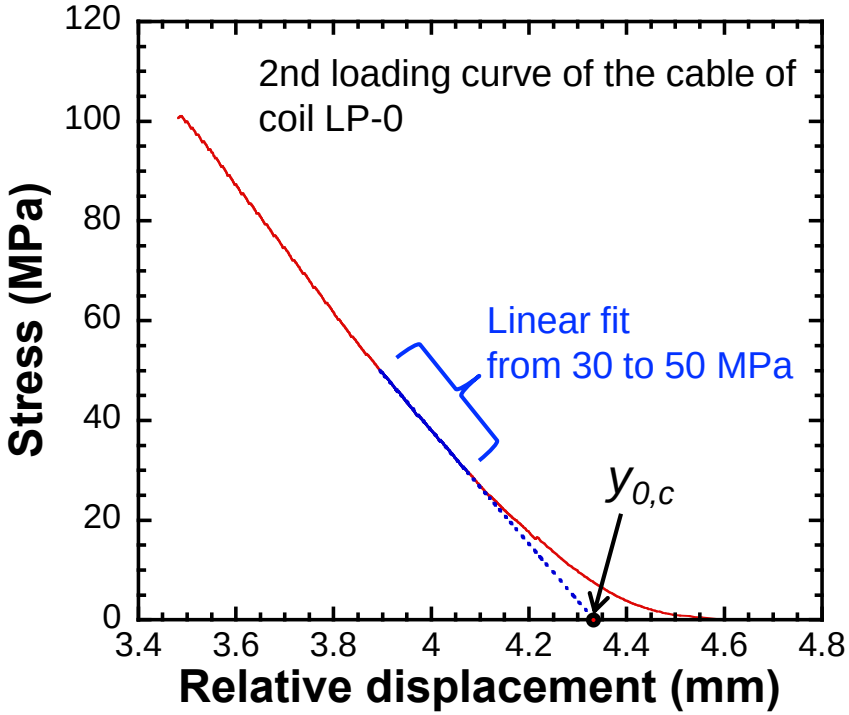
$$\Delta y_c = \Delta y_c^m - \Delta y_{Fe}^m + \frac{\sigma}{E} y_{0,Fe}$$

Measured values in Page 6

Calculated value

Data analysis: Initial thickness

Initial thickness ($y_{0,c}$) was determined in the following way.



- Non-linear initial part of the stress-displacement curve leads to ambiguity of $y_{0,c}$.
- In this analysis, $y_{0,c}$ was determined by extrapolating the linear fit of the curve from 30 to 50 MPa.

Thickness difference among LP-0, S2-1, S2-4 cable stack

22 cable stack thickness under 100 MPa (mm)

Coil ID	#1	#2	#3	Average	Stand. dev.
LP-0	38.573	38.523	38.538	38.544	0.026
S2-1	38.414	38.429	38.443	38.428	0.015
S2-4	38.394	38.397	38.422	38.404	0.015

Difference in cable stack thickness with respect to S2-4 cable (mm)

Coil ID	22 cable stack	44 cable stack
LP-0	+0.140	+0.280
S2-1	+0.024	+0.048

- The maximum scatter among three samples was ~ 50 μm for 22 cables, which is the limitation of the resolution in our measurement using the current setup.
- For 44 cables, LP-0 cable stack is 0.28 mm thicker than S2-4 cable stack.

Contribution of each factor to coil size difference

Magnet		MBXFS2	MBXFS3	MBXFP1	Remarks
Coil		S2-1	S2-4	LP-0	
Remark		Unused, remaining. Cable detachment after curing.	Assembled into MBXFS3	7 m long practice coil.	
Producer		KEK	KEK	Hitachi	
Coil stress at curing		~50 MPa	~50 MPa	80 MPa (?)	Fuji-paper measurement and expectation by hydrauric pressure.
Cross section		Type Model #2	Type Model #2	Type Prototype	Design by KEK
Relative coil size wrt S2-4. (in quad. coil)		+0.1 mm mm	0 mm	+0.5 mm	Both coils were measured at Hitachi in June 2020. Wrt S2-4 coil in MBXFS3, the difference for LP-0 coil is +0.5 mm. Difference between S2-1 and S2-4 can be explained by thickness of the bare cables (0.003 x 44=0.132 mm).
Difference wrt S2-4 coil or cable (in quad. coil)	1. Difference in design for all wedges (Page 6)	0 mm	0 mm	+0.06 mm	Drawing prepared by KEK.
	2. Actual size from design for all wedges by measurement (Page 6)	NA	0 mm	+0.06 mm at max	Report from Hitachi
	3. Difference in 44 cables with insulation (10-stack measurement) (Page16)	+0.05 mm	0 mm	+0.28 mm	Difference of 0.14 mm in stack measurement with 22 cables at KEK, June 2020.
1+2+3	Wedge size error + diff. of cable stack thickness	–	0 mm	+0.4 mm	Difference btw LP-0 and S2-4 = 0.4 mm
	Annex A. Difference in 44 cables w/o insulation. (Page 9)	+0.13 mm	0 mm	+0.13 mm	Data from CERN.
	Annex B. Difference in insulation tape thickness (Page 10)	0 mm	0 mm	0 mm	Measured by KEK

Contribution of each factor to coil size difference

Magnet		MBXFS2	MBXFS3	MBXFP1	Remarks
Coil		S2-1	S2-4	LP-0	
Remark		Unused, remaining. Cable detachment after curing.	Assembled into MBXFS3	7 m long practice coil.	
Producer		KEK	KEK	Hitachi	
Coil stress at curing		~50 MPa	~50 MPa	80 MPa (?)	Fuji-paper measurement and expectation by
Cro					
Relative coil size wrt S2-4. (in quad. coil)		+0.1 mm mm	0 mm	+0.5 mm	easured 2020. BXFS3, P-0 coil ference between S2-1 and S2-4 can be explained by thickness of the bare cables (0.003 x 44=0.132 mm).
Difference wrt S2-4 coil or cable (in quad. coil)	1. Difference in design for all wedges (Page 6)	0 mm	0 mm	+0.06 mm	Drawing prepared by KEK.
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1+2+3	Wedge size error + diff. of cable stack thickness	–	0 mm	+0.4 mm	Difference btw LP-0 and S2-4 = 0.4 mm
	Annex A. Difference in 44 cables w/o insulation. (Page 9)	+0.13 mm	0 mm	+0.13 mm	Data from CERN.
	Annex B. Difference in insulation tape thickness (Page 10)	0 mm	0 mm	0 mm	Measured by KEK

- Coil size difference by 0.4 mm between LP-0 and S2-4 can be explained by difference in wedge size and cable stack thickness.
- Remaining 0.1 mm can be due to uncertainty of 10 stack measurement.

Further plan

- KEK has received 19 Rutherford cables for D1 prototype and series. One of them has been used for the 7 m-long practice coil. KEK will perform 10 stack measurement for all the remaining cables.

- For mutual comparison, KEK will send the LP-0, S2-1, S2-4 cables to CERN for 10 stack measurement at CERN.

- KEK asked to CERN to send the newly insulated cable with a certain length to KEK for 10 stack measurement.

Supply of cables for prototype and series

- KEK needs at least 3 insulated cables to wind coils for a prototype. Coil winding will start in the middle of Aug. 2020. KEK prefers to receive the cables at the beginning of Aug. , so that KEK can conduct 10 stack measurement before sending the cables to Hitachi.

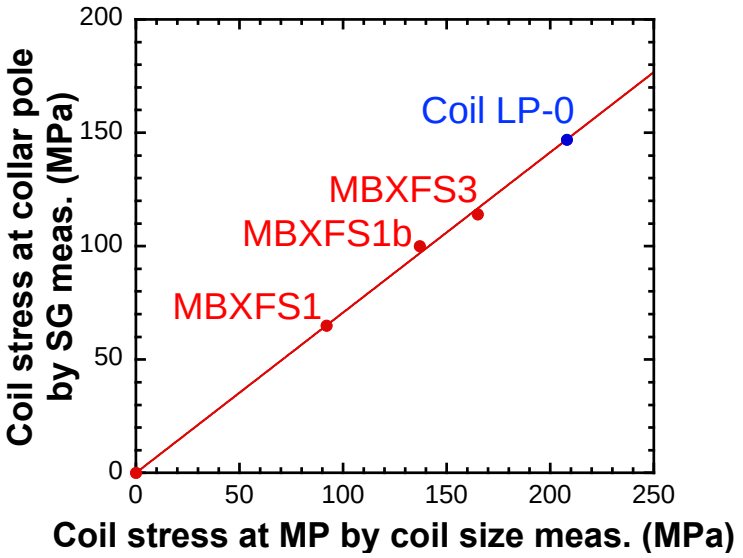
- KEK requests to CERN for re-insulating the remaining 18 cables.

Appendix

Influence of additional coil size on coil pre-stress

Azimuthal coil stress at the final size (MPa)

Magnet or Coil ID	Coil size meas. (extrapolated)	SG meas. at collar pole
MBXFS1	92	65
MBXFS1b	137	100
MBXFS3 (Coil S2-4)	165	114
Coil LP-0	208	147 (estimated)



- In the coil size measurement, coil stress is measured at MP, while strain gauge measurement shows the stress at collar pole.
- Linear relation between these two stresses was confirmed in the model magnets.
- Estimated stress at collar pole for coil LP-0 is 147 MPa. Pre-stress increase by additional coil size of 0.5 mm per quadrant is 33 MPa.
- Additional coil size of 0.1 mm → pre-stress increase of 7 MPa