eRMC assemblies and room-temperature preload

Autumn, 2019
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8. Room temperature preload
Shell instrumentation

- Fibers were also placed for strain monitoring at the locations:
  - S1MT
  - S2MT
  - S1MZ
  - S2MZ
  - S1CWT
  - S2CWT

Side 1 of the Shell faces the Jura.
Side 2 of the Shell faces Salève.

S2NCS detached and was fixed, but had to be reset to zero while the shell was not at zero stress (because of the yoke shims). Offset = -160 μstr.
Coil Instrumentation

A reset of all the coil strain gauges was performed prior to operation.

Fiber optic strain data available too for **C2MT**

Jura/right side. Goes with side 1 of shell

Salève/left side. Goes with side 2 of shell
Bladders and shims

10 mm yoke shims are used in the assemblies.

7.9—8.1 mm vertical shims are used (different shimming in each case).
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Fuji assembly 1 (FA1)

Placement of Fuji papers:

- **MS (10—50 MPa)** between the coil and the lateral pads
- **LLW (0.5—2.5 MPa)** between the two coils, in the magnet horizontal midplane
The lateral width of the coils was corrected with graded shimming kapton layers as shown.

### Deviation [mm], coil 1

<table>
<thead>
<tr>
<th>Z distance</th>
<th>LEFT</th>
<th>RIGHT</th>
<th>L+R</th>
<th>LEFT w Shim</th>
<th>Shim L</th>
<th>RIGHT w Shim</th>
<th>Shim R</th>
<th>L+R w Shim</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.052</td>
<td>0.104</td>
<td>0.156</td>
<td>0.102</td>
<td>0.050</td>
<td>0.104</td>
<td>0.206</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>0.074</td>
<td>0.066</td>
<td>0.140</td>
<td>0.099</td>
<td>0.025</td>
<td>0.091</td>
<td>0.025</td>
<td>0.190</td>
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<td>320</td>
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<td>0.052</td>
<td>0.102</td>
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<td>0.077</td>
<td>0.025</td>
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<td>420</td>
<td>0.062</td>
<td>0.057</td>
<td>0.119</td>
<td>0.087</td>
<td>0.025</td>
<td>0.082</td>
<td>0.025</td>
<td>0.169</td>
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<td>520</td>
<td>0.066</td>
<td>0.064</td>
<td>0.130</td>
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<td>620</td>
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<td>0.084</td>
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<td></td>
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<tr>
<td>720</td>
<td>0.069</td>
<td>0.074</td>
<td>0.143</td>
<td>0.094</td>
<td>0.025</td>
<td>0.099</td>
<td>0.025</td>
<td>0.193</td>
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<td>820</td>
<td>0.033</td>
<td>0.097</td>
<td>0.130</td>
<td>0.108</td>
<td>0.075</td>
<td>0.097</td>
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<td>0.115</td>
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<td>0.084</td>
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<td>0.190</td>
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<tr>
<td>1020</td>
<td>0.059</td>
<td>0.06</td>
<td>0.119</td>
<td>0.109</td>
<td>0.050</td>
<td>0.085</td>
<td>0.025</td>
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</tr>
<tr>
<td>1120</td>
<td>0.081</td>
<td>0.079</td>
<td>0.160</td>
<td>0.106</td>
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</tr>
<tr>
<td>1220</td>
<td>-0.118</td>
<td>-0.017</td>
<td>0.101</td>
<td>0.118</td>
<td>0.083</td>
<td>0.100</td>
<td>0.201</td>
<td></td>
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</tbody>
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### Deviation [mm], coil 2

<table>
<thead>
<tr>
<th>Z distance</th>
<th>LEFT</th>
<th>RIGHT</th>
<th>L+R</th>
<th>LEFT w Shim</th>
<th>Shim L</th>
<th>RIGHT w Shim</th>
<th>Shim R</th>
<th>L+R w Shim</th>
</tr>
</thead>
<tbody>
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<td>0.03</td>
<td>0.051</td>
<td>0.081</td>
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<td>0.206</td>
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<tr>
<td>220</td>
<td>-0.045</td>
<td>0.039</td>
<td>-0.006</td>
<td>0.055</td>
<td>0.100</td>
<td>0.139</td>
<td>0.100</td>
<td>0.194</td>
</tr>
<tr>
<td>320</td>
<td>-0.071</td>
<td>0.009</td>
<td>-0.062</td>
<td>0.054</td>
<td>0.125</td>
<td>0.134</td>
<td>0.125</td>
<td>0.188</td>
</tr>
<tr>
<td>420</td>
<td>-0.054</td>
<td>-0.027</td>
<td>-0.081</td>
<td>0.071</td>
<td>0.125</td>
<td>0.123</td>
<td>0.150</td>
<td>0.194</td>
</tr>
<tr>
<td>520</td>
<td>-0.04</td>
<td>-0.053</td>
<td>-0.093</td>
<td>0.060</td>
<td>0.100</td>
<td>0.122</td>
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<td>0.182</td>
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<tr>
<td>620</td>
<td>-0.05</td>
<td>-0.096</td>
<td>-0.146</td>
<td>0.075</td>
<td>0.125</td>
<td>0.129</td>
<td>0.225</td>
<td>0.204</td>
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<tr>
<td>720</td>
<td>-0.011</td>
<td>-0.097</td>
<td>-0.108</td>
<td>0.064</td>
<td>0.075</td>
<td>0.128</td>
<td>0.225</td>
<td>0.192</td>
</tr>
<tr>
<td>820</td>
<td>-0.006</td>
<td>-0.102</td>
<td>-0.096</td>
<td>0.056</td>
<td>0.050</td>
<td>0.123</td>
<td>0.225</td>
<td>0.179</td>
</tr>
<tr>
<td>920</td>
<td>-0.013</td>
<td>-0.117</td>
<td>-0.104</td>
<td>0.063</td>
<td>0.050</td>
<td>0.133</td>
<td>0.250</td>
<td>0.196</td>
</tr>
<tr>
<td>1020</td>
<td>0.048</td>
<td>-0.1</td>
<td>-0.052</td>
<td>0.073</td>
<td>0.025</td>
<td>0.125</td>
<td>0.225</td>
<td>0.198</td>
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<tr>
<td>1120</td>
<td>0.036</td>
<td>-0.006</td>
<td>0.030</td>
<td>0.061</td>
<td>0.025</td>
<td>0.119</td>
<td>0.125</td>
<td>0.18</td>
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<tr>
<td>1220</td>
<td>-0.194</td>
<td>-0.254</td>
<td>-0.448</td>
<td>0.056</td>
<td>0.250</td>
<td>0.121</td>
<td>0.375</td>
<td>0.177</td>
</tr>
</tbody>
</table>
Attempts to introduce (9,9). Couldn’t get to 9 mm in the Jura side.

173 bar, all but except Salève bladders.

175 bar at Jura bladders to remove Jura shim.

Coil pack is loose.

(9,0) (8.7,8.8) (8.7,8.9) (8.8,8.9) and afternoon break (9.0,8.9) (9.0,9.0) (0,0) V bladders to remove top vertical shims V bladders to remove lower vertical shims Shim legend: (Salève, Jura)
FA1 results

Saturated areas (stainless steel)

Shimming marks
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8. Room temperature preload
Fuji assembly 2 (FA2)

Placement of Fuji papers:

MS (10—50 MPa)

- between the coil and the lateral pads.
- also between the two coils, in the magnet horizontal midplane. Expect it whiter than in FA1.
Coil shimming for FA2

The shims of the coils during FA1 have been removed. Now we attempt to place a uniform (along the coil) kapton shimming to avoid the edge marks seen in the FA1:
History of operation

Attempt with 130 bar in yoke + Salève bladders to insert another 9-mm in the Salève side. Enters halfway through. We increase the pressure a bit more.

Inserted 9-mm shim in the Jura side: (0,9)

Yoke and Salève bladders

(9,9)

Y+J to remove Jura shim

Y+S to remove Salève shim

vshims removed

vshims inserted
FA2 results compared to FA1

Connection side

Jura side, Fuji1:

Jura side, Fuji2:

Salève side, Fuji1:

Salève side, Fuji2:

Non connection side

white areas around the transition endshoe-coil

white areas around the transition endshoe-coil
Coil x stress

Coil stresss

Stress $\sigma_x$ [MPa]

Time [s]

C1MT
C2MT
C1CST
C2CST
C1NCST
C2NCST
Observations after FA2

SHELL
- In general, a normal behavior of the strain gauges. Little longitudinal stress. S2NCS gauge just has its initial offset.

COIL
- C1MT and C2MT behaved normally during the operation.
- The axial strain observed are particularly high.
  E.g., C2M: $\varepsilon_x = -40, \varepsilon_z = +90$; C1CS: $\varepsilon_x = -190, \varepsilon_z = +125$;
- A bit high values in the CS, both in X and Z.
- Something weird with C2MT upon disassembly, reads 120 $\mu$str. An issue with the connector of its wire was then identified and fixed by Sohrab

FUJI
- Better looking with this shimming, but a few areas were not marked, near the beginning of the endshoes.
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Preload attempt 1 to 50% transversal

Attempted to preload the magnet for operation to around 50% of transversal targets. Performed 16 and 17th of October 2019.

With the newest FEM model to that day(*), the targets (50%) were:

- around 250 $\mu$str (18 MPa) at the shell.

- around -110 $\mu$str in the coil center (steel post) and 200 in the extremities (Ti), which is around around 20 MPa.

-Expected to be reached with 300—400 microns of interference.

(*)Because of a reformulaiton of the contacts of ANSYS, the model has been afterwards updated and the final targets now are different.
Results shell midplane

Effect of yoke shims visible up to interference = 0.2 mm
Good agreement with FEA in the slope. However the gauges fall up to 100 μstrain higher, the same happened with the dummy structure study.
Results shell 45°

Effect of yoke shims visible up to interference = 0.2 mm
Excellent agreement with FEA, same as with dummy coils.
Coil 2 visibly less loaded than coil 1.
Steel (red) and titanium (black) seem to be getting same deformation, against predictions.
Important offsets at 0 interference ➔ bending
Transfer functions - $\varepsilon$

All points fall around the same line, whereas a difference was expected.
Read stress in the center falls slightly below. But still not good enough.
Issues encountered

The results in the coils were not as expected.

- The analysis of the axial values yielded Poisson ratios of up to 20:1.

- Coil 2 less loaded than Coil 1

- The steel and titanium parts of the pole show the same strain, where we would spect a ratio of about 1.7

Possibly having issues of coil bending and bad contact with lateral pad.

**Proposed action** ➔ Reduce the vertical keys from 8.1 to 8.0 mm should decrease significantly the effects of the bending. We do another preload attempt.
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History of operation

Shim legend:
(Salève, Jura)

Horizontal shimming is (9.4,9.4)

Vertical bladder operation to go to v keys = 8.0 mm
Top v shims changed to 8.0
Bottom v shims changed to 8.0
Inserting the yoke shims
Fixing one of the bladders. From now on only bladders of 1 side are operated (before it was symmetrical), less pressure is thus needed.
Disassembly

Bladder pressure history

Pressure [bar]

Time [s]
Results shell midplane

At 0.5 mm of interference we remove the yoke shims. This is why there are 2 values for each gauge at that point. This will happen in the following charts too. Good agreement with FEA in the slopes.
Results shell $45^\circ$

A bit worse match with the FEA than before, but still fair.
Results coil

Coil 2 middle totally unaffected.
A bit of offset in the extremities, but really good slope overall. The offsets are less than in the previous case.
Transfer functions – ε

The circled points correspond to readings with the yoke shims. Much better fit in the case of the extremities (Ti). Still there is a lot of spread in the coil values. The slope of the points of the center is too low due to the C2MT gauge which wasn’t being much affected.
Transfer functions $- \sigma$

The circled points correspond to readings with the yoke shims. Much better fit in the case of the extremities (Ti). Still there is a lot of spread in the coil values. The slope of the points of the center is too low due to the C2MT gauge which wasn’t being much affected.
Coil $\varepsilon$ and $\sigma$ with time

This is to highlight the evolution of C2MT particularly, which had had issues before and its wire was re-solded before the operation. We observe that it does react to bladder operation.
Observations

- Coil measurements really much affected by the vertical interference.
- Possibly causing bending in the pole and affecting the readings in the pocket area.
- The coil strain readings are then tricky to trust.
- This is highlighted by these preloads, the only difference between them was 8.1 vs. 8.0-mm vertical keys inserted:

![Graphs showing coil middle strain vs. shell azimuthal strain with 8.1-mm and 8.0-mm vertical shims.](image-url)
Observations

- Coil bending was reduced by reducing the vertical shimming.
- Still the contact is poor and entails local losses of load in the coil.
- The kapton shimming corrections were not enough to correct the coil sizes and ensure good contact.

- The coils shall be machined laterally to flatten their surface and improve contact, because they are not equal. Coil 2 was nearly flat at the center *SS parts (even with 8-mm vertical keys.
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5. Preload attempt 2
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Preloads before machinining

- Preloads were executed on eRMC magnet.
- The coil bending could be counteracted by reducing the vertical shimming.
- Still the contact is poor and entails local losses of load in the coil. Coil 2 saw less stress than coil1.
- Coils to be machinned laterally to flatten their surface and improve contact, because they are not equal.
- To reduce the lateral rails by an amount that would make the coils have the same width and to each side (centering in the post): $L_1 = R_1 = L_2 = R_2$.
- We take, thus, the smallest (most negative) deviation which happens in C102 (ignoring the points located in the end shoes, i.e., at $z = 20$ mm and $z = 1220$ mm).
Coil size, L and R deviations

Alignment done to the central post

Coil 101

Coil 102
Critical coil, 102

- Minimum L/R deviation is -0.270 mm reference
- Coil width (as per drawings) 257.7 mm
- Target L+R coil width after machining
  \[256.7 - 2 \times 0.270 = 256.16 \text{ mm}\]

As we take the post as reference, this means a target \( L = R = 128.08 \text{ mm} \)
Machinining

- C101 machinned the 6/12/19 (many of you were having an awesome lunch 😊).
- C102 machinned the 9/12/19
Machinning

- C101 machinned the 6/12/19. C102 machinned the 9/12/19
Machining results

Deviations before machining

Deviations after machining

CERN

1/27/2020
Machinining results

- C102 seems a bit asymmetric (possible misalignment while machinning) but its L+R is excellent:

The target is -0.27 mm, max deviation (high) is + 13.5 μm and min deviation (low), is – 11 μm, this is below the precision of the FARO.
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6. Measuring and machining of the coils
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8. Room temperature preload
Fuji assembly 3 (FA3)

- Low vertical shimming this time (7.9 mm) due to double-layer LLW paper.

The placement of Fuji papers is the same as it was in FA1:

- MS (10—50 MPa) between the coil and the lateral pads
- LLW (0.5—2.5 MPa) between the two coils, in the magnet horizontal midplane
FEA comparison, shell

*Based on the machining and the results, the estimated interference is corrected by 200 microns.

More loaded in the center than in the extremities, but mostly OK especially with the slope.
FEA comparison, coils

*Based on the machining and the results, the estimated interference is corrected by 200 microns,

Reasonably good results
Transfer functions

Good fit (within spread range) of the extremities (Ti parts of the pole)

The SS center is still somewhat unloaded with respect to the FEA predictions.
Fuji papers

Non connection side

LLW (0.5—2.5 MPa)

Connection side

#101 Right (Jura)

#101 Left (Salève)

#102 Right (Jura)

#102 Left (Salève)

MS (10—50 MPa)
Observations

COIL
- C2MT started to react now a bit (in the previous assemblies it did not do it at all).
- Better behavior, overall, than before.
- Still a large spread in CCS/CNCS.
- Still the straight part (red dots) fall far above the FEA predictions

FUJI
- Excellent marks for coil 1. A few voids in coil 2
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Shimming plan for preload

For the RT preload, it is decided to place 125-μm kapton shimming between the coil rails and the lateral pad alongside the straight part of the conductor (i.e., not shimming the coil ends) in order to increase a bit the pressure in the middle. For both coils, left and right.

125-μm kapton shims
Preload and operation targets

With 625 microns of lateral interference and rods at 181 kN (each) at RT preload:

a) We have small coil-pole detachment…

b) …while keeping the coil below 150 MPa of von Mises.
Preload and operation targets

The magnet is highly friction-dominated: the coil displacement during the power up ($\Delta u_z$) depends little on the axial preload.

Decided to preload with SS rods to reach about 80% of the axial L.F at 16T (100% is 370 kN, so around 293 kN -per magnet quadrant-).

Thus, the RT preload targets are:

### TABLE III: Axial displacement of conductor $\Delta u_z$ during powering and force repartition

1. *High preload* scenarios are targeted to a tie-rod force equal to approximately the 100% of the L.F. (370 kN per magnet quadrant, one tie-rod per quadrant) at the powering stage, whereas the *mid preload* scenario targets the 80% instead.
2. *Ideal* scenarios with no friction nor end-plate bending.

<table>
<thead>
<tr>
<th>$\Delta u_z$ [µm]</th>
<th>Al rods</th>
<th>SS rods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>123</td>
<td>119</td>
</tr>
<tr>
<td>Average</td>
<td>93</td>
<td>89</td>
</tr>
<tr>
<td>Max($^2$)</td>
<td>399</td>
<td>285</td>
</tr>
<tr>
<td>Average($^2$)</td>
<td>371</td>
<td>247</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% of EM forces</th>
<th>82/43/-25</th>
<th>101/26/-27</th>
<th>79/46/-25</th>
<th>100/27/-27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rods/structure/coils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% transversal, no axial</td>
<td>0.3125</td>
<td>-3.5</td>
<td>-3.5</td>
<td>3.3</td>
</tr>
<tr>
<td>50% transversal and axial</td>
<td>0.3125</td>
<td>-24.8</td>
<td>-23.7</td>
<td>20.4</td>
</tr>
<tr>
<td>100% transversal 50% axial</td>
<td>0.625</td>
<td>-24.7</td>
<td>-23.5</td>
<td>20.5</td>
</tr>
<tr>
<td>100% transversal and axial</td>
<td>0.625</td>
<td>-47.7</td>
<td>-45.0</td>
<td>39.4</td>
</tr>
</tbody>
</table>
History of operation

Started without lateral interference, 8.0-mm vertical keys, and around 10 μstr of traction in the SS rods.

Removed the yoke shims using 139 bar.

Here additional bladders were mounted in lieu of the yoke shims. These bladders are used onwards. As well as the axial traction system, it was mounted here too.

50% of the transversal target was reached in the shell at (9.5,9.5). Here we reached 50% axial with the rods, i.e., 142 μstr.

Axial work to finish the preload.
Results, shell

*Based on the machining and the results, the estimated interference is corrected by 200 microns,

Reached the targets in the coil center (red). In the extremities, (black) we stayed a bit behind.
Results shell 45°

Based on the machining and the results, the estimated interference is corrected by 200 microns,
Results, coils

We did not reach the target values in the coils. The preload was stopped nonetheless because the targets were reached in the shell.

*Based on the machinining and the results, the estimated interference is corrected by 200 microns,
Transfer function, $\varepsilon$

Coil middle strain ($\mu$strain) vs. Shell azimuthal strain ($\mu$strain). With yoke shim and targets.

FEA SS — Red squares
SS — Red triangles
FEA Ti — Black squares
Ti — Black triangles

Targets are indicated on the graph.
Transfer function, $\sigma$

![Graph showing coil middle stress vs. shell azimuthal stress for different materials (FEA SS, SS, FEA Ti, Ti) with yoke shim and target points.](image-url)
Rods

<table>
<thead>
<tr>
<th>Rods</th>
<th>End μstr</th>
<th>End MPa</th>
<th>End kN</th>
<th>End % L.F.</th>
<th>Target MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rod A</td>
<td>314</td>
<td>62.8</td>
<td>202</td>
<td>54.59</td>
<td>57</td>
</tr>
<tr>
<td>Rod B</td>
<td>327</td>
<td>65.4</td>
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<td>56.89</td>
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<tr>
<td>Rod C</td>
<td>325</td>
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<tr>
<td>Rod D</td>
<td>316</td>
<td>63.2</td>
<td>203</td>
<td>54.95</td>
<td>57</td>
</tr>
</tbody>
</table>
Observations

- Still the coil seems to see less stress/strain than predicted. The same happened with the dummy assembly.

- Target load for the shell was reached at the center (red points). For the extremities we fell a bit behind.

- The trends in the coil flatten after reaching the 50% of the target. However the shell still increases steadily, discarding the possibility of yielding. Possible bending? Pocket effect?

- Better overall behavior with the coils machined than before.

- Estimated schedule: eRMC now undergoing last warm preparations. To be cooled down at the end of this week or next Monday.
Thank you for your attention!