Analysis of the Training Behaviour of the MICE Spectrometer Solenoid

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Introduction

- MICE: Muon Ionization Cooling Experiment
- Beamline presently collecting data at Rutherford Appleton Laboratory, UK
- Part of MICE: tracker magnets
  - large bore solenoids
  - NbTi, 4T on-axis field
  - Each tracker consists of five solenoids (Fig. 1)
- Training: 15 quenches necessary
  - Usually E2 quenches (both trackers)
  - Both tracker magnets do not 'remember' training
  - Thermal cycling: re-train magnets

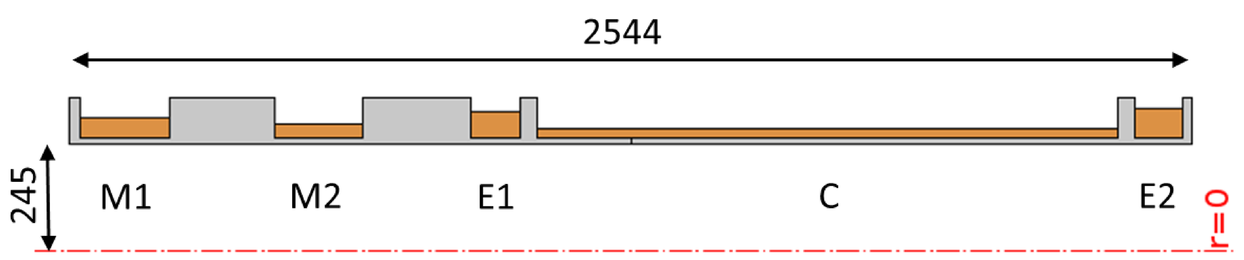

Figure 1: Geometry of the MICE spectrometer solenoid. All dimensions in *mm*.

- Not obvious that margin is issue (70–80% at first quench)
- Investigate other potential issues
- Approach: 2D/3D FEA
  - COMSOL Multiphysics
  - Use contact elements between coil and bobbin
  - Load steps: wire-pretension → cool-down → Lorentz force
  - Quasi-static and transient

Geometry

- Coil bobbin: Al-6061-T6
  - Facilitates quench-back
- Inner/outer radius: 245/350 mm

Table 1: MICE Coil Configuration

	r_i (m)	dr (m)	z_1 (m)	dz (m)	J (A/mm^2)
M1	0.258	0.0462	-3.7116	0.2012	118
M2	0.258	0.0309	-4.1508	0.1995	142
E1	0.258	0.0609	-5.8582	0.1106	149
SS	0.258	0.0221	-5.8582	1.3143	148
E2	0.258	0.0678	-6.0063	0.1106	148

Training History

- Re-training: similar training curves

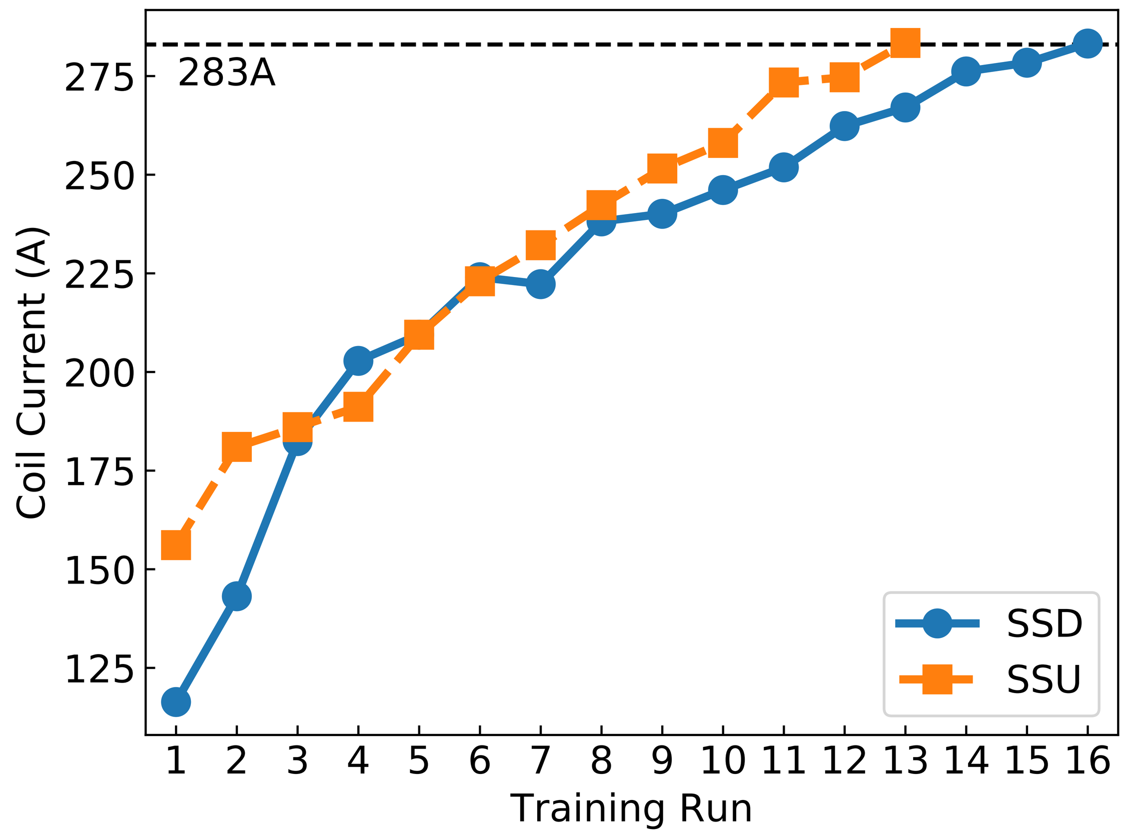

Figure 2: Training history of the MICE spectrometer solenoids.

Initial Cool-down

- Al: thermal expansion coefficient twice as large
- Coils detach from bobbin
- Each coil held longitudinally by Al-bobbin
- E2/M1: lower flange detaches from coil
- E2 held less strongly in place than other coils
- Focus on E2 for further analysis

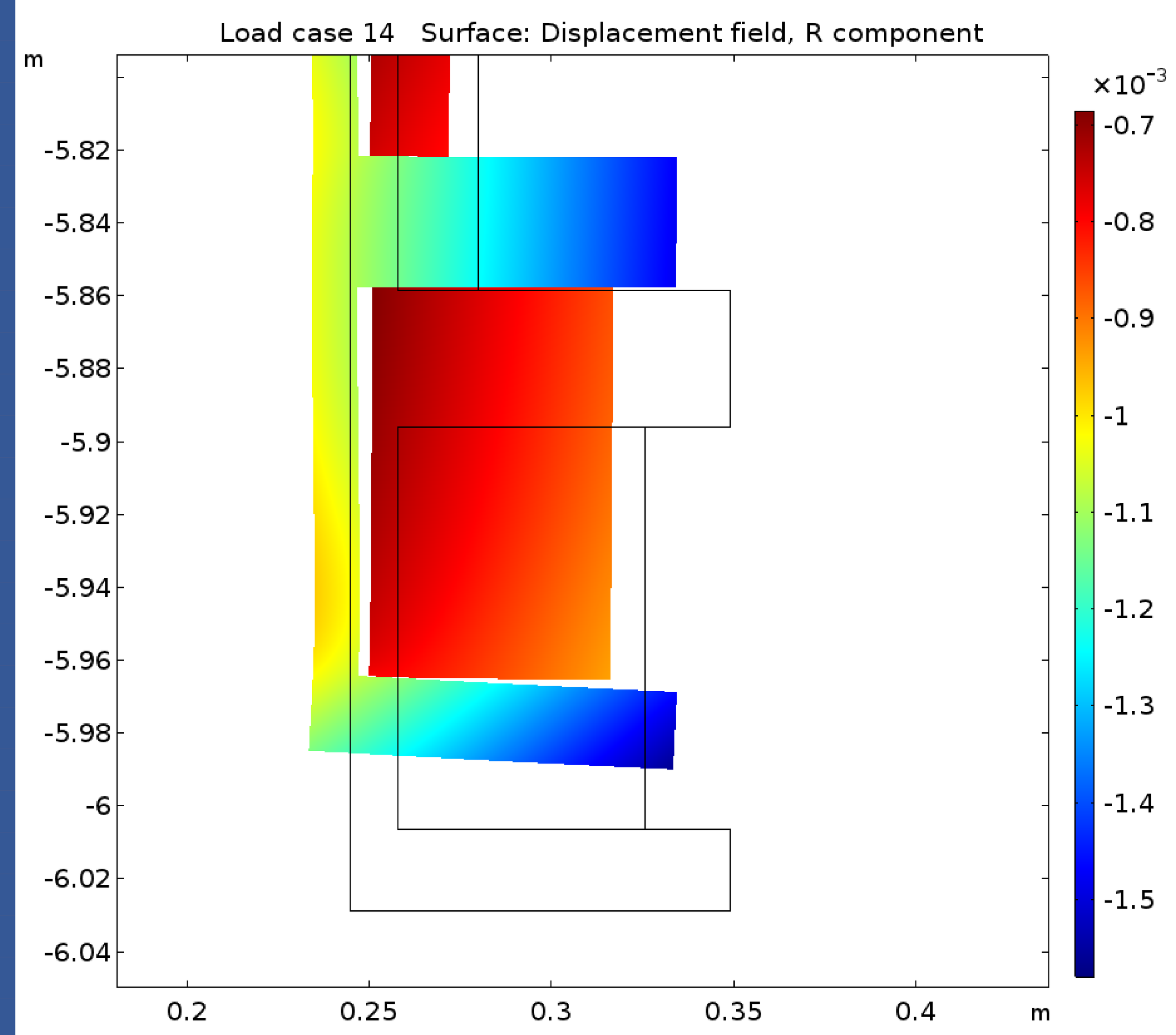

Figure 3: Deformation plot of the E2 coil and the bobbin (deformation ten times amplified). The colour indicates the radial displacement.

Lorentz Force

- Quasi-static simulation: apply 25%, 40%, 60%, 80% and 100%
- 10% load steps, reduce to zero in-between
- Radial displacement of E2 coil shown in Fig. 4
- Coil slips out of its pocket
- M1 coil: similar, but not as severe
  - E2: additional longitudinal force, pulling E2 to C coil (1.6 MN)

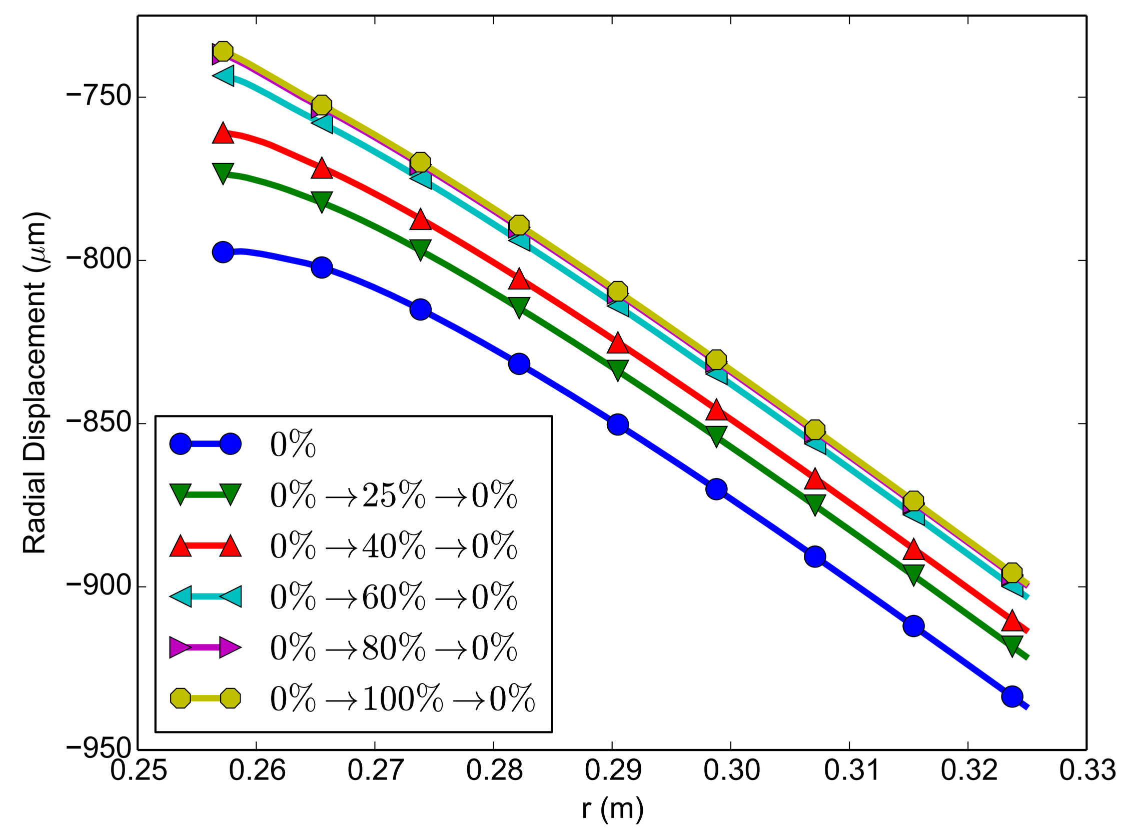

Figure 4: Radial displacement of the lower E2 boundary for various mechanical load scenarios.

- Focus on E2: time-dependent study (arbitrary time-base, no inertial effects)
- Simulation suggests that displacement cannot be expected to be smooth
- $t/T_0 = 0.15$ and 0.275: jumps in radial displacement

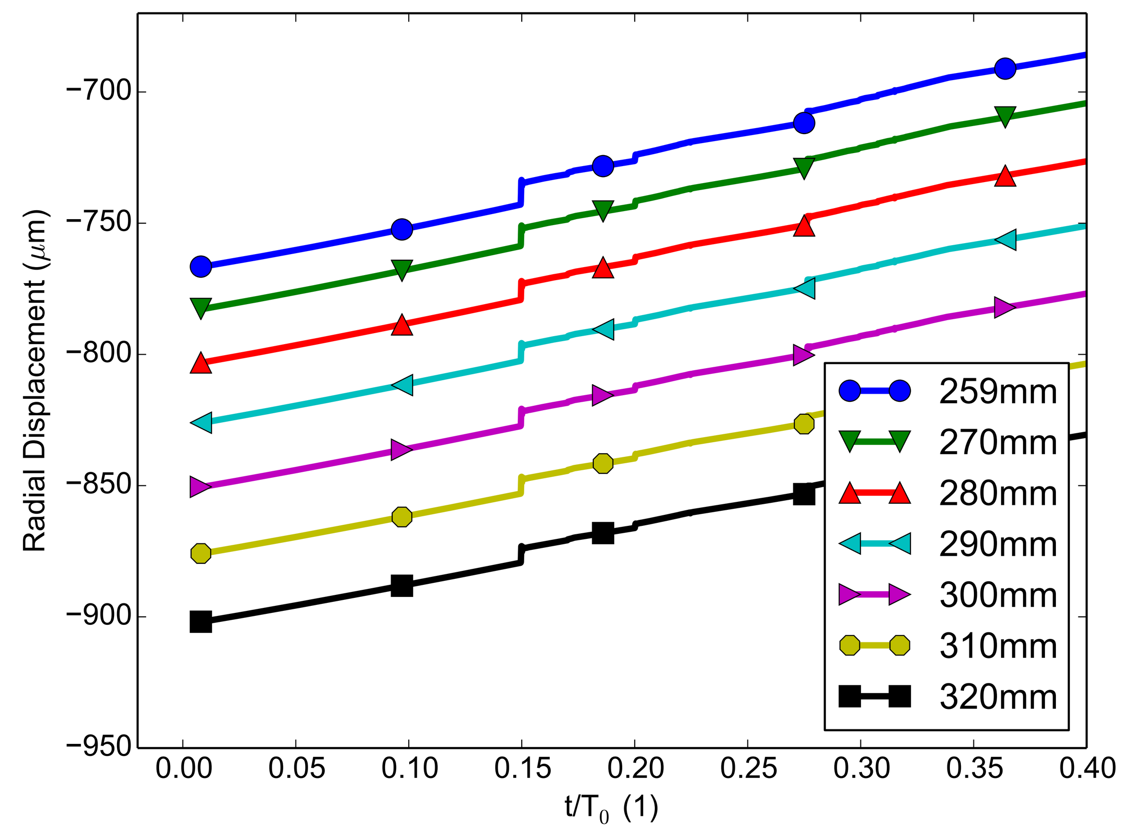

Figure 5: Time dependent radial displacement of different points on the lower E2 boundary.

Thermal Cycling

- Warm-up: coils return to original positions
- Sub-sequent cool-down: identical to initial cool-down
- True for all coils
- Fig. 6 shows radial displacement for E2 coil

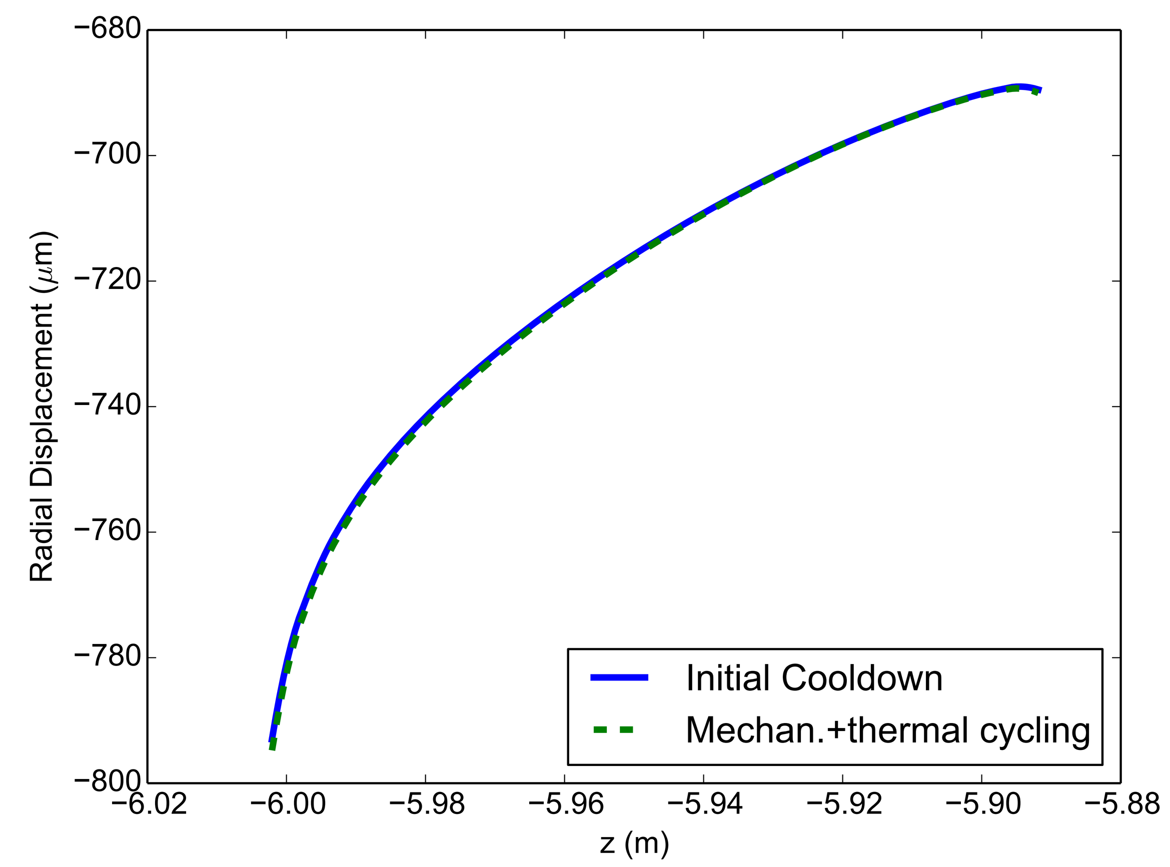

Figure 6: Radial displacement of the inner radius of the E2 coil for the initial cool-down and after mechanical and thermal cycling.

Improvements

- Coil geometry can be optimized to increase temperature margin
- Steel bobbin: similar thermal expansion coefficient to NbTi
- Coil movement during operation: minimize with sufficient wire pre-tension (120 MPa)
- Stick-slip scenario not observed in this case

Conclusion

- Different thermal expansion coefficients: bobbin shrinks at different rate than NbTi solenoids
- Coils detach from bobbin
- Coils held longitudinally by flanges
- E2/M1: coils partially detach from flange
- Lorentz-force: coils can slip in coil pocket (shown for E2)
- Stick-slip → heating → can trigger quench
- Thermal cycling: resets coils (consistent with observation)