Imperial College London

Magnet Commissioning at Step IV

J. Pasternak

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Introduction

- MICE experiment aims to demonstrate the muon ionization cooling necessary for future muon beams (for the Neutrino Factory, a Muon Collider and next generation muon experiments).
- The full demonstration of the ionization cooling requires to pass muons both through an absorber material (LH_2, LiH, etc.) and re-accelerating system (RF cavities). This will be done at Step V/VI.
- In MICE Step IV beam passage through the absorber will be studied, but nevertheless several important experimental goals can be achieved:
  - Observation of a decrease of normalised emittance (cooling)
  - Test of phase space reconstruction muon by muon
  - Study of optics in the MICE channel
  - Measurement of muon stopping/straggling and multiple scattering
- In order to achieve this plan we need to successfully and efficiently commission magnets in the MICE channel.
- MICE Magnets Integration Task Force has been created and is working on the magnet commissioning procedure.

MICE Channel at Step IV (1)

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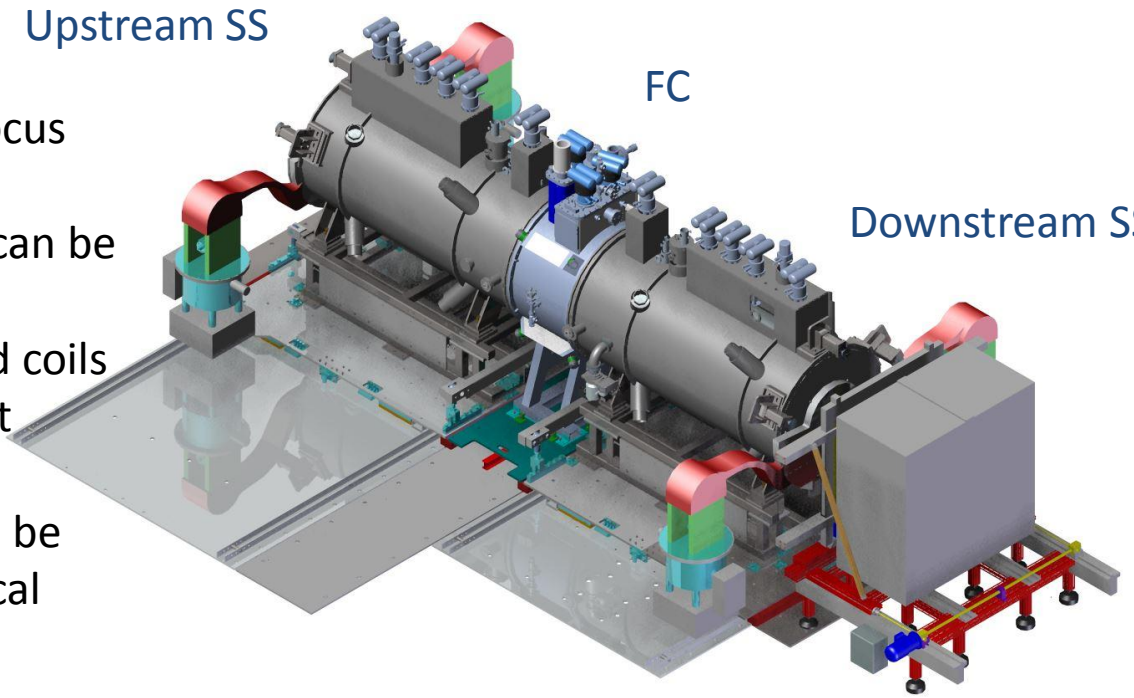
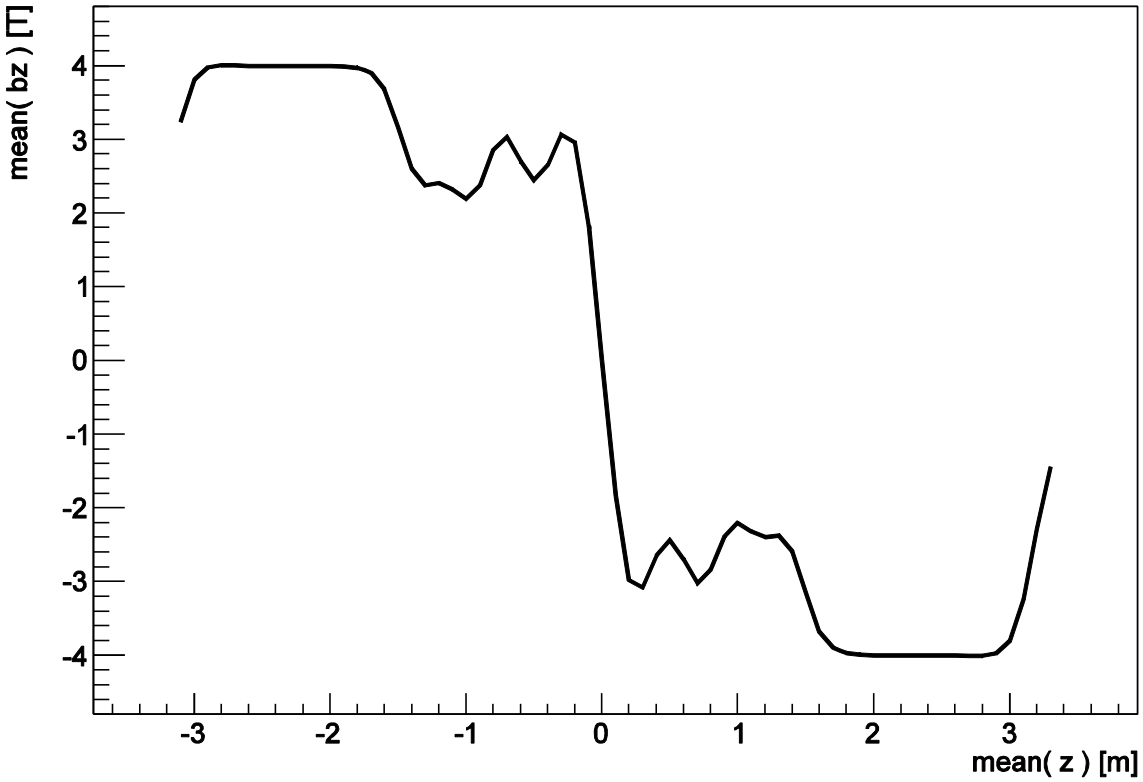
- MICE channel at Step IV uses 2 Spectrometer Solenoids (SS) and 1 Focus Coil (FC).
- It contains 12 coils, out of which 11 can be independently powered.
- Although the SS coil Central and End coils will be most likely operated at current values close to the nominal ones, the currents in Matching Coils and FC will be considerably varied defining the optical settings.



Case	p (MeV/c)	β (cm)	B (T)	Coil currents (A)					
				E2	C	E1	M2	M1	FC
Nom. FC I	200	24	4	253	274	234	193.1	210.6	188
Red. FC I	200	29	4	253	274	234	193.1	219.5	167.3
Red. FC I+A	200	29	4	253	274	234	193.1/176.7	219.5/200.8	167.3
Nom. β	200	42	4	253	274	234	224	214.5	133.9
Nom. β	240	42	4	253	274	234	218.3	269	150.6
Nom. β	140	42	4	253	274	234	188.5	141	100.4

Magnet settings for the flip mode)

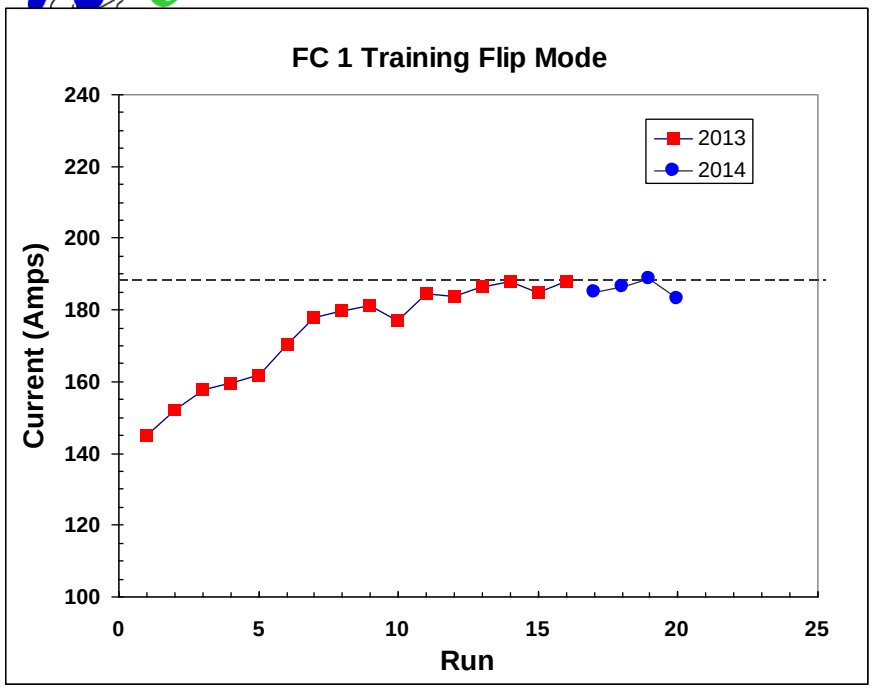
MICE Channel at Step IV (2)

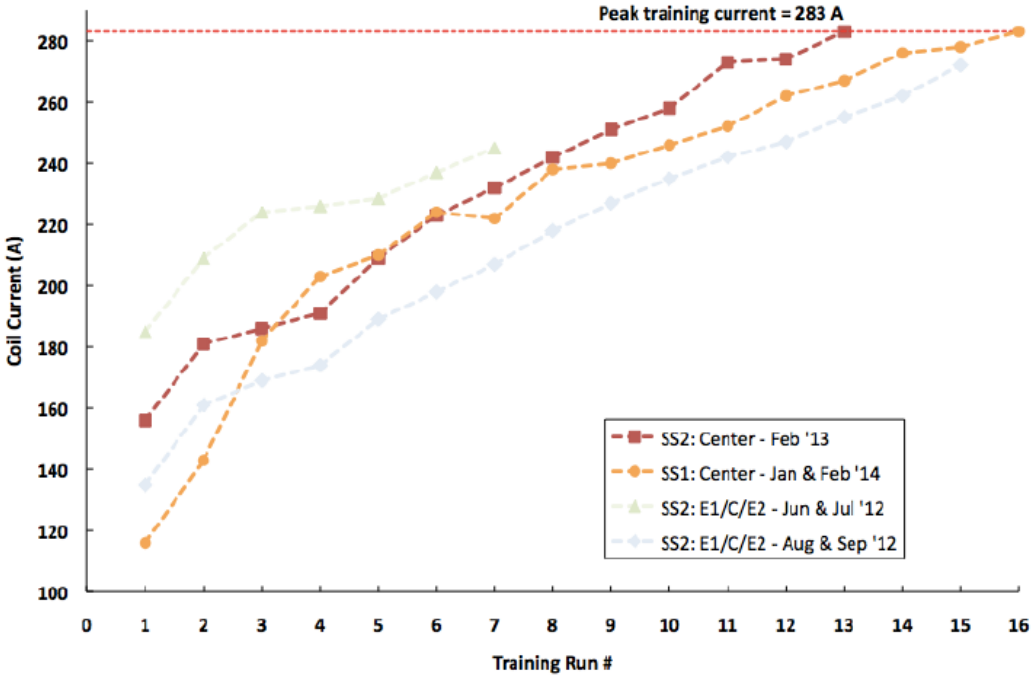


Typical magnetic field on axis in one of baseline configurations.

- Coils in MICE channel are of large aperture and some are also short in length.
- They will be positioned relatively close to each other.
- This will result in a strong magnetic coupling!

MICE Channel at Step IV (3)





- Both SS and FC have been trained.
- SSs do not remember their training.
- FC does remember the training in the flip mode.
- It is estimated to require ~15 quenches to reach the nominal SS's currents.
- This needs to be taken into considerations for the commissioning procedure in particular taking into account a mutual couplings between the magnets.

Requirements for the Magnet Commissioning

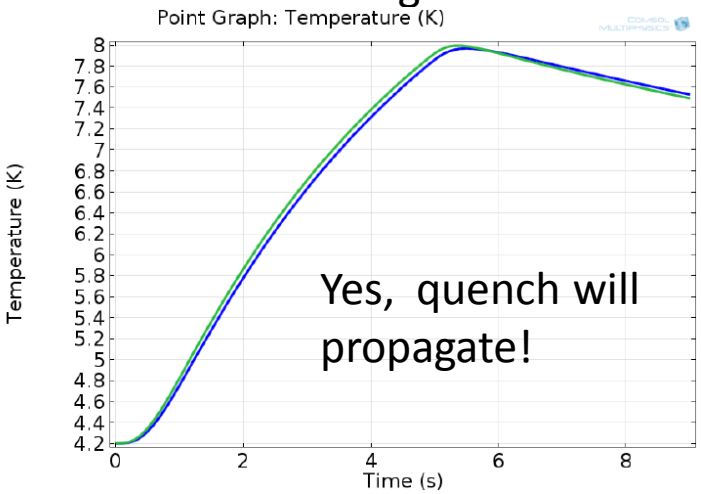
- The ambitious goal is to achieve stable operation at 180 A in FC (achieved stable operation) with nominal SS settings.
  - ❑ Testing maximal currents in M1 and M2 coils.
- The realistic goal may be to achieve stable operation at derated FC current of 165 A with sufficient margins in currents for M1 and M2 for tuning freedom.
  - ❑ This will provide us with sufficient flexibility for beam operation (data taking).
- Commissioning will also establish the necessary standards and knowledge required for operations
  - ❑ How to tune the channel
  - ❑ How to switch on/off
  - ❑ How to go from one setting to the other

Commissioning Scenarios Considered by Magnet Integration Task Force

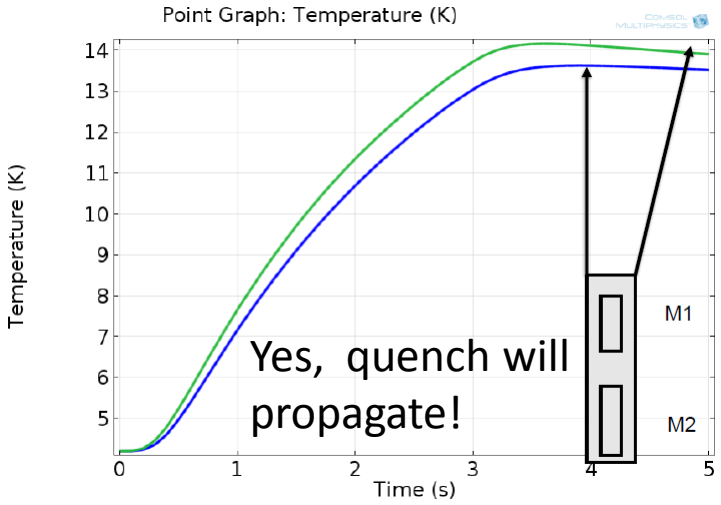
- **Scenario 1: Independent training at start**
  - ❑Once assembled in the MICE channel perform independent training of each magnet (both SS with ~15 quenches each and FC with ~3 quenches).
  - ❑Once all magnets reached their independent nominal settings, perform combined training of the entire channel raising the currents in all magnets simultaneously (as some more quenches may occur due to a new force distribution).
- **Scenario 2**: Variation of Scenario 1 allowing for simultaneous training of both SSs at the beginning (with currents present in both SS at the same time).
- **Scenario 3**: **Combined training at start**
  - ❑Once assembled in the MICE channel perform combined training of the entire channel raising the currents in all magnets simultaneously.
- **Scenario 4**: Mixture of Scenarios 1 and 3
  - ❑ Start with combined training, once quench-back effects occur, continue training magnets individually.
  - ❑Make the combined training of all magnets at the end.
- **Scenario 5: Independent training at start + Experimental Approach at the combined phase**
  - ❑Once assembled in the MICE channel perform independent training of each magnet.
  - ❑Once all magnets reached their independent nominal settings, set nominal current in both SSs and start raising current in the FC. Monitor the entire channel. Further steps depend upon experimental findings.

Quench back issues

Does quench of one module trigger quench of neighbour modules (via eddy currents heating in Aluminium mandrels)?



FC temperatures induced by SS quench

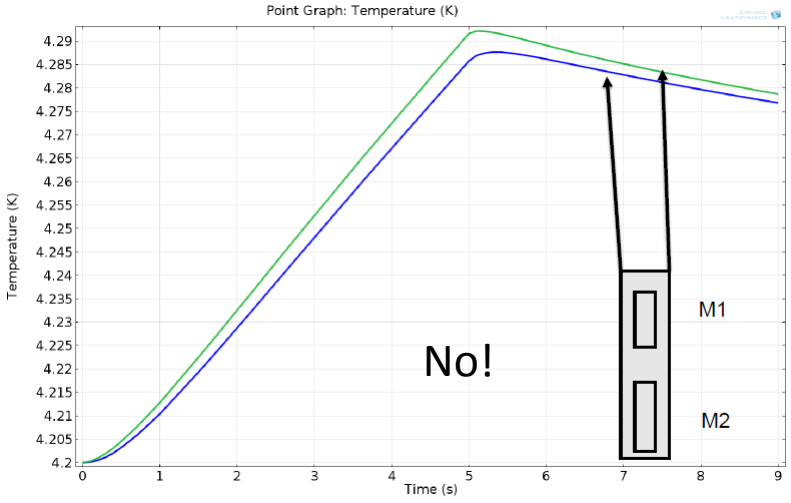


Yes

SS (M1,M2) temperatures induced by FC quench

- Coupled multiphysics analysis (E-M and thermal)
- Material properties taken into account
- Magnet switch-off times: FC 3s and SS 5s.
- Conclusion:

Quench induced via eddy currents heating will propagate through the MICE channel, if FC is switched on.



SS (M1,M2) temperatures induced by the second SS quench

Quench propagation issues

- Does quench of one SS trigger quench of second SS (via inducing a fake quench signal in the Quench Detection (QD) system triggering the quench event)?
- We need the inductance matrix at Step IV geometry:

	E2	SS	E1	M2	M1	FC	FC	M1	M2	E1	SS	E2
E2	12.241	3.690	0.053	0.022	0.019	0.025	0.017	0.004	0.002	0.002	0.004	0.001
SS	3.690	42.227	3.297	0.533	0.262	0.230	0.134	0.024	0.010	0.009	0.022	0.004
E1	0.053	3.297	10.001	0.934	0.285	0.167	0.084	0.013	0.005	0.004	0.009	0.002
M2	0.022	0.533	0.934	6.356	1.033	0.318	0.132	0.017	0.006	0.005	0.010	0.002
M1	0.019	0.262	0.285	1.033	14.326	1.825	0.541	0.051	0.017	0.013	0.024	0.004
FC	0.025	0.230	0.167	0.318	1.825	81.302	12.848	0.541	0.132	0.084	0.134	0.017
FC	0.017	0.134	0.084	0.132	0.541	12.848	81.302	1.825	0.318	0.167	0.230	0.025
M1	0.004	0.024	0.013	0.017	0.051	0.541	1.825	14.326	1.033	0.285	0.262	0.019
M2	0.002	0.010	0.005	0.006	0.017	0.132	0.318	1.033	6.356	0.934	0.533	0.022
E1	0.002	0.009	0.004	0.005	0.013	0.084	0.167	0.285	0.934	10.001	3.297	0.053
SS	0.004	0.022	0.009	0.010	0.024	0.134	0.230	0.262	0.533	3.297	42.227	3.690
E2	0.001	0.004	0.002	0.002	0.004	0.017	0.025	0.019	0.022	0.053	3.690	12.241

All values in H

(SS should be C here according to the notation used in this presentation)

• Using the above inductance matrix, assuming SS at nominal currents and switch off time of 5s, the voltages induces in the second SS coils can be estimated (in linear approximation):

$(V_{E2}, V_C, V_{E2}, V_{M2}, V_{M1})=(0.6, 3.2, 1.5, 1.8, 4.9)$ [V]

• As this values are similar to the thresholds set in QD system, quench of one SS may induce quench in the second SS via triggering its Quench Protection (QP) system.

Assumptions for the magnet commissioning

- A quench in any of the magnets will result in the full MICE channel quench event.
- Quench may propagate between SSs even if FC is off.
- The 48h minimal time between quenches for the FC sets the recovery time for the MICE channel (SSs can quench 1,2 times per day).
- This allows to estimate the time duration and LHe requirements for various scenarios.

Commissioning Scenarios
Recommendations by Magnet Integration Task Force

- **Scenario 1: Independent training at start**
  - ❑Independent training phase may require ~29 day and ~17000 l of LHe (40% contingency included).
  - ❑This is our strong backup!
- **Scenario 2**: Variation of Scenario 1 allowing for simultaneous training of both SSs at the beginning (with currents present in both SS at the same time).
  - ❑Not recommended due to a presence of inductive coupling.
- **Scenario 3**: **Combined training at start**
  - ❑ Assuming all quenches are uncorrelated it may require ~92 days and ~42000 l of LHe
  - ❑ Not recommended (inefficient).
- **Scenario 4**: Mixture of Scenarios 1 and 3
  - ❑Complicated in operation and may also be inefficient.
  - ❑Not recommended
- **Scenario 5: Independent training at start + Experimental Approach at the combined phase**
  - ❑The same cost for the individual phase as Scenario 1
  - ❑It will allow to quickly assess the situation (how far we are from the nominal operation?)
  - ❑**Recommended by the Task Force.**

Recommended Scenario for MICE magnets commissioning at STEP IV (1)

- Magnets will be installed, connected and a ramping test completed in advance.
- Sufficient supply of LHe needs to be secured
  - ❑ Discussions with BOC indicate Liquid Helium availability will not be an issue!
  - ❑ It is recommended that each magnet will be equipped with its own dewar
- It will be followed by individual magnet training
  - ❑ SS will be trained in parallel, but, only 1 magnet will be ramped at a time (1 quench per magnet per day and 2 quenches per day in 24/7 training operations).
  - ❑ We will start most likely in flip mode.
- Once all magnets reached their independent nominal settings, set nominal current in both SSs and start raising current in the FC.
  - ❑ Detecting which coil quenches first knowing the FC current will allow to assess how far we are from the nominal setting:
  - ❑ Depending on experimental findings the procedure may be followed by:
    - ❑ Training the FC with SS currents fixed at nominal (repeating the procedure).
    - ❑ Training the FC with SS currents fixed at derated value (to be defined).
    - ❑ Switching to combined training (Scenario 1 with ramping all magnets simultaneously at approximately 2.5 quench per week incl. 40% contingency)

Additional Recommendations for MICE magnets commissioning at STEP IV

- Test of power supplies and QD/QP systems needs to be performed in advance.
- All magnets needs to be individually quench protected at all times.
- Forces induced on PRY needs to be monitored by observing the displacement
  - ❑ Studies indicate that for nominal settings and magnets powered individually forces are acceptable.
  - ❑ Scheme to monitor displacement is being considered.

Conclusions

- Scenarios for magnet commissioning at Step IV have been considered by the MICE Magnets Integration Task Force.
- We have established a feasible scenario, which we are recommending->We have the plan!
- It is clear that strong magnetic coupling will make commissioning a challenging task, but we are confident we are prepared to deal with it!
- We need to start thinking about the beam commissioning.

Acknowledgements

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