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PARTIAL RETURN YOKE FOR MICE STEP IV AND FINAL STEP*

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Abstract

This paper reports on the progress of the design and construction of a retro-fitted return yoke for the international Muon Ionization Cooling Experiment (MICE). MICE is a proof-of-principle experiment aiming to demonstrate ionization cooling experimentally.

In earlier studies we outlined how a partial return yoke can be used to mitigate stray magnetic field in the experimental hall; we report on the progress of the construction of the partial return yoke for MICE Step IV.

We also discuss an extension of the Partial Return Yoke for the final step of MICE; we show simulation results of the expected performance.

INTRODUCTION

Ionization cooling has been discussed for a long time for applications where particles need to be accelerated quickly. Ionization cooling so far has never been demonstrated experimentally; MICE is an experiment which is presently constructed at the Rutherford Appleton laboratory in the UK to demonstrate this for the first time [1].

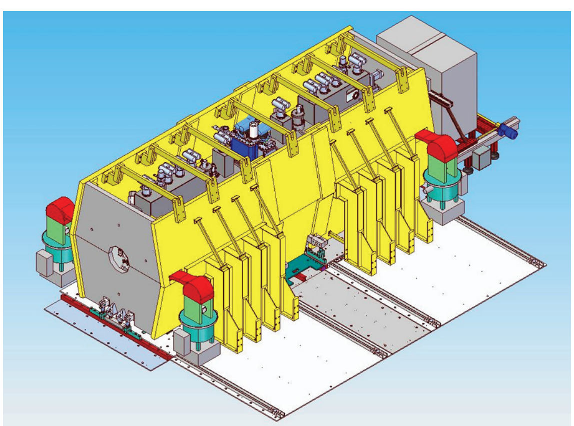

Figure 1: The MICE Partial Return Yoke.

At the time of writing MICE Step IV is under construction, which consists of 12 superconducting solenoids. Recently it was discovered that the MICE solenoids produce a substantial stray magnetic field, which can be problematic for equipment in the MICE hall.

To mitigate this risk the concept of the so-called Partial Return Yoke (PRY) was developed. The MICE PRY is a retro-fitted return yoke, which partially encloses MICE. Figure 1 shows the PRY surrounding the MICE solenoids in Step IV configuration.

In earlier papers we have described the concept, the expected shielding performance and the engineering [2–4]. This paper reports on the progress of construction, which includes magnetic testing of the low-carbon steel for the yoke and required adjustments of the MICE coil currents. The paper concludes with a concept of the extension of the PRY for the final step of MICE.

MATERIAL

For the MICE PRY a low carbon steel (C content $< 0.010\%$) was chosen because of the high saturation value in combination with a high relative magnetic permeability. The design of the PRY was carried out with magnetization curves supplied by the manufacturer. About 60 metric tons of 10 cm thick plate material was obtained; from each heat samples were taken.

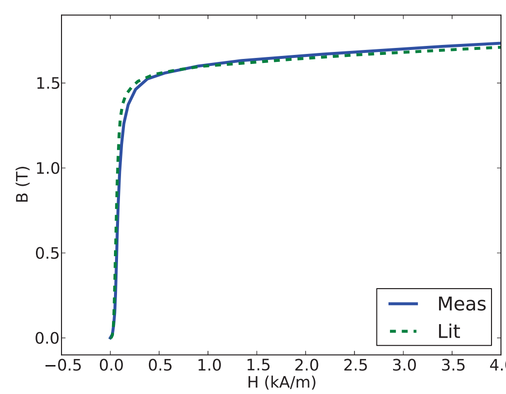

Figure 2: Comparison of the measured and literature magnetization curves of the MICE PRY low carbon steel.

The magnetization curves of the samples were measured by a commercial supplier; it was found that very little difference was observed between the different heats. Figure 2 shows the measured data in comparison to the initially used literature values and Fig. 3 the calculated relative magnetic permeability. As shown in the figures, there is a small variation of the material properties at small magnetic fields. At the operating point of the MICE PRY, which is indicated by the dashed line in Fig. 3, the measured permeability agrees well with the expected value. Simulations show that the differences in material properties lead to a change of the stray magnetic field in the MICE hall by about 1 Gauss (0.1 mT).

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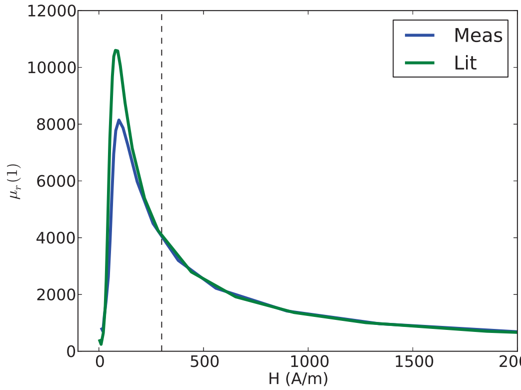

Figure 3: Comparison of the measured and literature values of the relative magnetic permeability of the MICE PRY low carbon steel.

CORRECTION OF THE MICE COIL CURRENTS

The MICE solenoids were originally designed without the presence of a return yoke. Due to the presence of the iron the MICE solenoids produce a higher on-axis field for the same current (~%). To correct for this the currents in the MICE solenoids need to lowered.

Table 1: MICE Coil Geometries in *m*

	r_i	r_o	d_z	z_1
E2	0.258	0.324	0.1106	-6.0063
SS	0.258	0.2793	1.3143	-5.8582
E1	0.258	0.3176	0.1106	-4.5063
M2	0.258	0.2878	0.1995	-4.1508
M1	0.258	0.3027	0.2012	-3.7116
FC	0.263	0.347	0.21	-3.06

A fast way to determine the required corrections is by assuming that the errors are a perturbation to the original field. The perturbation assumption is valid as small changes in the coil currents will not significantly change the magnetization in the PRY.

Table 2: MICE 240 MeV/c Coil Currents in A/mm^2

	Flip No PRY	Sol No PRY	Flip PRY	Sol PRY
E2	152.44	135.18	144.28	128.18
SS	135.18	152.44	133.88	151.39
E1	127.37	127.37	126.1	126.73
M2	151	133.39	149.58	132.84
M1	142	142.85	141.19	142.63
FC	137	71	136.97	70.867

This means that the system can be treated as linear, which greatly simplifies the calculation. In practise the required correction currents are calculated by setting up a system of linear equations. A point is chosen in each solenoid at its centre; the matrix elements correspond to the fields at each of these points for a unit current of 1A. By solving this system of linear equations for the error field the required correction can be obtained.

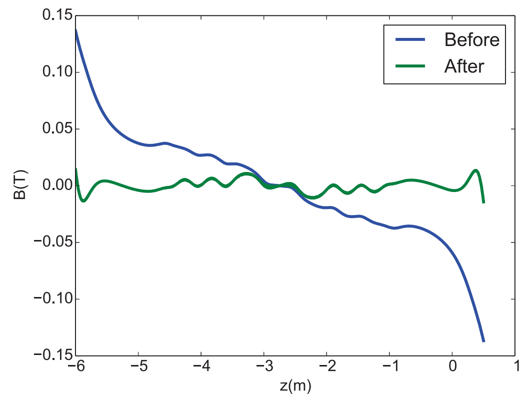

Figure 4: Deviation of the longitudinal field from the ideal field without iron for the 240 MeV flip mode.

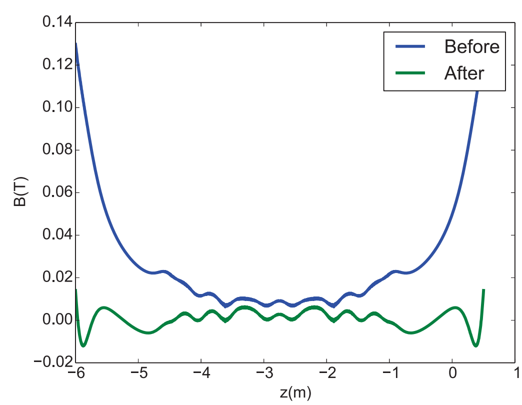

Figure 5: Deviation of the longitudinal field from the ideal field without iron for the 240 MeV solenoid mode.

Figures 4 and 5 show the error fields before and after correction; Table 2 shows the coil current densities before and after correction (the coil geometries are shown in Table 1; in the table r_i and r_o are the inner and outer radii, z_1 the longitudinal position of the upstream magnet corner and d_z the coil length).

INSTALLATION PRY STEP IV

At the time of writing the south side of the PRY is installed in the MICE hall. Figure 6 shows the installation of one of the centre sections in March 2015.

The remaining parts of the PRY are expected at RAL end of April; installation will commence in May 2015.

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Figure 6: Installation of the MICE PRY south side in the MICE hall.

MICE FINAL STEP

After the successful completion of MICE Step IV the construction of the final step of MICE will commence, which extends MICE by another absorber focusing module (AFC) and RF cavities. The geometry of the final step of MICE is described in [5].

As the MICE channel grows longitudinally, the PRY needs to be modified. A conceptual design of the PRY for MICE Final Step is shown in Fig. 7. As shown in the figure, the mid-section of the PRY is replaced with a longer version. Due to the relatively small current density in the focusing coils of the AFC (about 85 A/mm^2) no additional modifications are required.

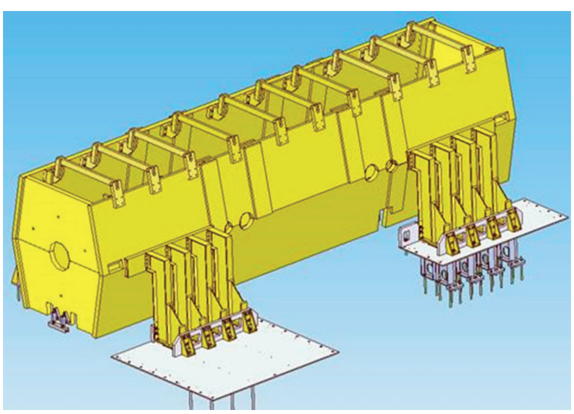
Figure 7: Conceptual Design of PRY for MICE Final Step.

The expected shielding performance is shown in Fig. 8. The figure shows isometric surfaces of 5 and 10 Gauss (0.5 and 1 mT). The simulation result shows that similarly to the PRY of Step IV good shielding performance is obtained behind the shielding walls, whereas some flux is leaking out at the top and bottom of the PRY which is not shielded.

The magnetization in the new centre section is relatively low; the forces were evaluated in a finite element simulation using the Maxwell stress tensor. The force on each of the new centre sections was found to be less than 3 kN (in horizontal direction). Additional support legs may be required to restrict the floor loading to an acceptable level.

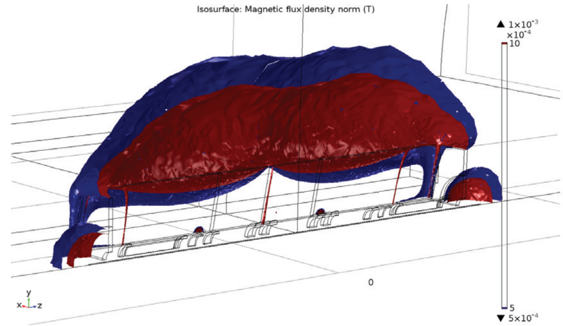

Figure 8: 5 and 10 Gauss isometric surfaces for MICE Final Step.

CONCLUSION

The construction of the MICE PRY is well underway and is expected to be finished as planned in May 2015. Magnetic measurements of the samples of the PRY steel show the expected performance; we therefore expect a shielding performance close to earlier predictions.

The necessary adjustments to the MICE solenoid currents to cancel effects of the PRY have been calculated using a fast and simple approach; using the corrected coil currents the on-axis field matches the envisaged field well.

For the final step of MICE the PRY can be extended by replacing the centre section; due to the relatively low fields in that area we do not forsee any problems with the shielding performance.

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