PARTIAL RETURN YOKE FOR MICE – GENERAL CONCEPT AND PERFORMANCE*

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Abstract

MICE, which is an acronym for Muon Ionization Cooling Experiment, is a technology demonstration which is presently assembled at the Rutherford Appleton Laboratory in Didcot, UK. MICE aims to demonstrate ionization cooling experimentally, which is an essential technology for potential future accelerators such as a muon collider.

The MICE channel consists of up to 18 large bore superconducting solenoids, which produce a substantial stray field. This stray field can jeopardize the operation of electrical and electronic equipment in the MICE hall.

The concept of a partial flux return yoke has been developed, which reduces the stray field in the MICE hall to a safe level. This paper discusses the general concept and expected performance.

INTRODUCTION

Ionization cooling can be regarded as an essential technology for future HEP particle accelerators such as the muon collider, as it is the only known technology fast enough to reduce the emittance of a muon beam.

MICE, which aiming to demonstrate the concept [1], will be assembled in several steps. At the time of writing it is aimed to finish construction of Step IV by summer/autumn 2014. MICE Step IV consists of 12 large bore superconducting solenoids. The MICE solenoids produce a substantial amount of stray field (in excess of 50 mT), which is a concern as some of the technical equipment in the MICE hall may not work.

This paper discusses the design concept of a partial return yoke (PRY) for the MICE solenoids for Step IV. The engineering design is described in [2, 3].

METHODOLOGY

For the analysis of the problem and performance estimate two commercial finite element packages are employed: COMSOL Multiphysics (COMSOL AB, Tegnergatan 23, SE-111 40 Stockholm, Sweden) and Opera 3D from Cobham/Vectorfields (Cobham CTS Limited trading, 24 Bankside, Kidlington, Oxfordshire, OX5 1JE, UK).

The two software packages use different physics implementations, which allows to verify the obtained results. COMSOL solves for the magnetic vector potential:

$$\nabla \times \left(\mu^{-1} \nabla \times A\right) = J \ . \quad (1)$$

In this equation μ is the magnetic permeability, A the magnetic vector potential and J a current density. In contrast to this Opera 3D solves for the magnetic scalar potential ϕ:

$$\nabla\mu\nabla\phi - \nabla\mu\left(\int_{\Omega_J} \frac{J \times R}{|R^3|} \mathrm{d}\Omega_J\right) = 0 \ . \quad (2)$$

Contributions to the magnetic field from current carrying structures at a distance R are usually evaluated using Biot-Savart law and integrated over the domain Ω.

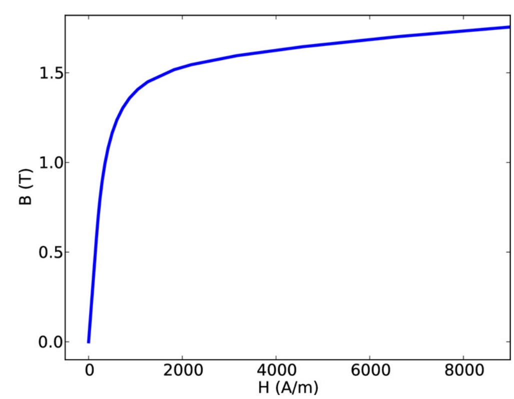

Figure 1: Magnetization curve of AISI 1010 steel.

For the simulations we assume that shielding iron will have the magnetic properties shown in Fig. 1. The magnetization curve was taken from Opera and is valid for AISI 1010 steel.

The coil geometries used in the simulation are summarized in Table 1.The MICE solenoids will be run in five different configurations. In two configurations the magnetic field flips in the centre of the MICE channel ('flip modes') whereas in three it does not ('solenoid modes'). The current densities for all cases are summarized in Table 2.

GENERAL CONCEPT

All MICE magnets are large diameter solenoids, which are relatively thin and short. From a shielding point of view an ideal solution is to encase the MICE magnets in a soft-iron cylinder. This is of course not practical; however, it is possible to achieve good shielding by only encasing MICE partially in this way. Fig. 2 shows the concept.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.
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ISBN 978-3-95450-138-0

Table 1: Step IV, Coil Geometries

	z1 [m]	z2-z1 [m]	r1 [m]	r2 [m]
1	-6.0063	0.1106	0.258	0.324
2	-5.8582	1.3143	0.258	0.2793
3	-4.5063	0.1106	0.258	0.3176
4	-4.1508	0.1995	0.258	0.2878
5	-3.7116	0.2012	0.258	0.3027
6	-3.06	0.21	0.263	0.347
7	-2.65	0.21	0.263	0.347
8	-1.99	0.2012	0.258	0.3027
9	-1.549	0.1995	0.258	0.2878
10	-1.1104	0.1106	0.258	0.3176
11	-0.956	1.3143	0.258	0.2793
12	0.3967	0.1106	0.258	0.324

Table 2: Step IV, Current Densities in A/mm^2

Coil No.	Flip 1	Flip 2	Sol 1	Sol 2	Sol 5
1	-135	-135	135	135	135
2	-152	-152	152	152	152
3	-127	-127	127	127	127
4	-137	-151	55	66	16
5	-119	-142	62	71	44
6	-114	-137	60	71	113
7	114	137	60	71	113
8	119	142	62	71	44
9	137	151	55	66	16
10	127	127	127	127	127
11	152	152	152	152	152
12	135	135	135	135	135

As shown in the figure, the MICE PRY covers an azimuthal angle of about $\pm 60°$ just outside of the cryostats. The remaining parts are left unshielded because of spatial constraints. In practice the MICE PRY consists of eight 1.5 m wide and 4 m long iron plates. For the thickness we consider two cases: 10 cm, which is the nominal case, and 12 cm which offers a better shielding performance. Each shielding plate is tilted by $11.5°$ towards MICE to satisfy spatial restraints and to aid the shielding efficiency. In longitudinal direction the PRY is completed by additional shielding plates which connect the two side halves of the PRY (apart from a small opening with radius 250 mm for the beam).

PERFORMANCE

The magnetization in the PRY is equivalent to a magnetic field 1.1T for all operational modes of MICE Step IV. At this level the relative permeability of the shielding iron is about 1700–2000, which was found to be sufficient to suppress flux leakage.

Fig. 3 shows the stray magnetic field at a radius of 1.5 m at beam height, which is about 10 cm radially away from

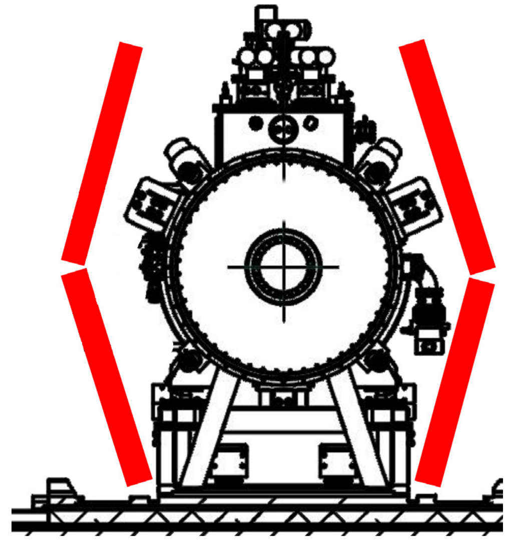

Figure 2: General Concept, frontal view. The partial return yoke is shown schematically in red.

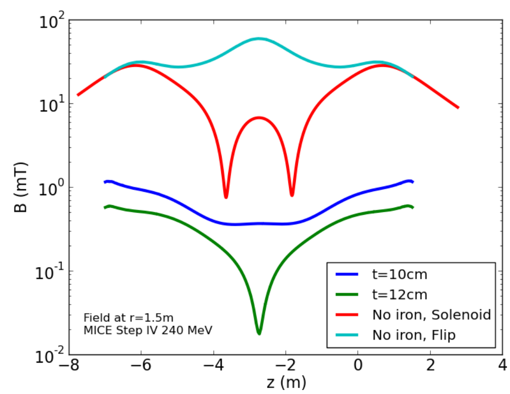

Figure 3: Modulus of the magnetic fringe field at a radius of 1.5 m at beam height.

the PRY. The figure shows a comparison between two unshielded cases (240 MeV flip and solenoid mode) and two shielded cases (solenoid mode). The two shielded cases differ in the thickness of the shield, which is 10 or 12 cm.

As shown in the figure, the PRY is effective in reducing the field level to 0.6–1.1 mT depending on the chosen thickness. This is a reduction by more than 50 to the unshielded case, where the stray fields are between 30–70 mT.

Fig. 4 visualizes the 5 Gauss line in 3D. The 5 Gauss line is important because of health and safety considerations. Shown is a comparison between the unshielded (left) and shielded case (right figure). The figure emphasizes that the fringe field extent is significantly reduced. In longitudinal direction the 5 Gauss line is reduced from about 13 to 8 m. In horizontal direction the 5 Gauss line finishes with the PRY, which is located at about 1.4 m. In vertical direction, which is not covered by the PRY, the 5 Gauss line is moved from 4.5 m to about 2 m.

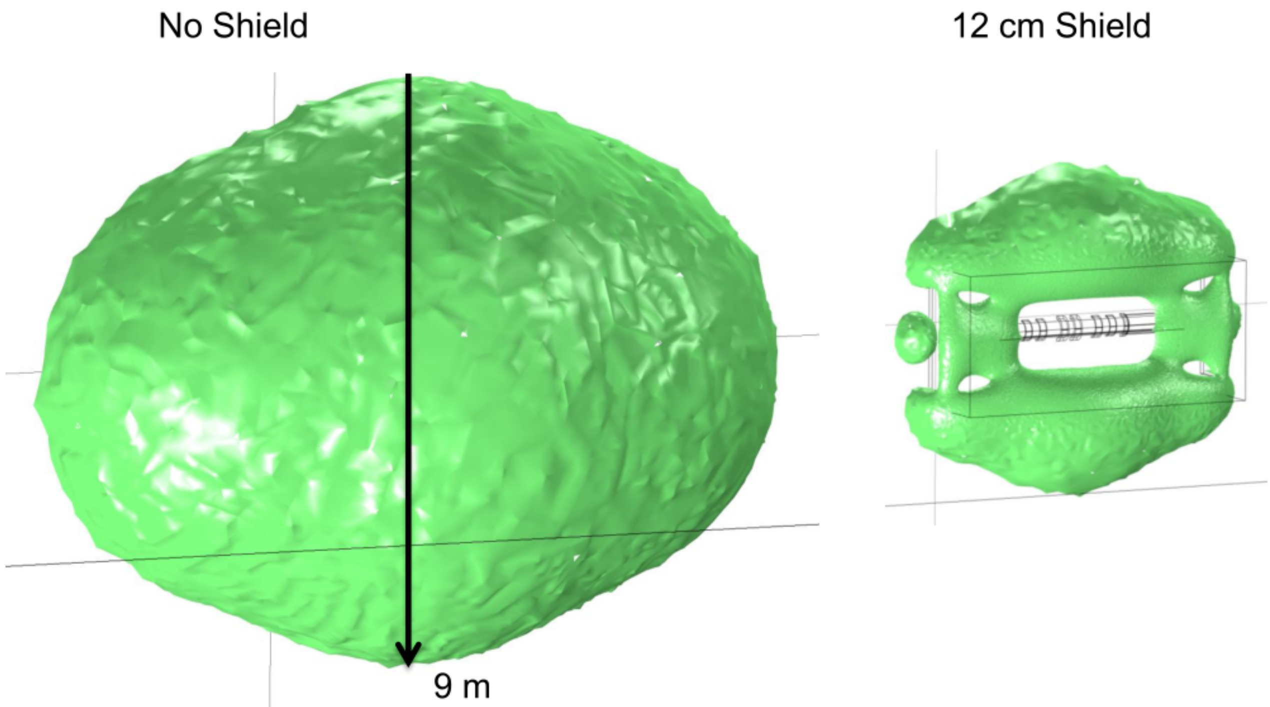

Figure 4: 5 Gauss iso-surface plot of MICE for the 200 MeV flip mode. The left figure shows the 5 Gauss surface for an unshielded scenario (no iron present) versus the case where the PRY is adopted.

EFFECT ON THE BEAM

The additional iron in close proximity to MICE changes the magnetic field in the channel. A particular concern is the asymmetry of the PRY due to the fact that in vertical direction MICE is unshielded. This leads to an asymmetric error field which can be detrimental for the performance of MICE. A particle tracking study using MAUS (MICE Analysis User Software) was carried out to address this [4].

The simulation consisted of 100,000 muons; simulated was the 200 MeV case (flip mode). It was found that due to the error field the mean beam position is shifted by about 100 µm, the beta function changes by about 10 mm and the discrepancy between emittances is about 1 µm.

The results indicate that the changes introduced by the MICE PRY have a barely measurable effect and therefore do not compromise the experiment.

SUMMARY

This paper outlines a shielding concept for the international Muon Ionization Cooling Experiment MICE, which is capable of reducing the stray fields in the MICE hall to a tolerable level. The MICE channel will not be encased fully due to spatial constraints, but the as shown the shielding performance is still sufficient to shield large parts of the MICE hall.

Two different shield thicknesses were studied; in comparison to a 10 cm thick PRY a 12 cm version reduces the stray magnetic field at a radius of 1.5 m by a factor of two or more and offers therefore more margin.

Simulation results suggest that the 5 Gauss line in the MICE hall in horizontal and longitudinal direction would be located just after the PRY. In vertical direction the distance to the 5 Gauss line is reduced by about a factor of 2.

The effect on the beam was studied using particle tracking simulations and it was found that the effect of the additional iron is negligible.

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ISBN 978-3-95450-138-0