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TRANSIENT MAGNETODYNAMIC FINITE ELEMENT ANALYSIS OF THE ISIS M25/2 10 Hz KICKER MAGNET

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Abstract

In 2007 a second target station (TS2) was added to the ISIS pulsed neutron source at RAL. Two slow kicker magnets are operated in order to direct a 10 Hz proton beam towards TS2 through the TS2 Extract Proton Beam line (EPB2). When first manufactured and tested, the M25/2 exhibited unforeseen magnetic and thermal behaviour. It was quickly identified that this was caused by the eddy currents induced in the laminated core and the mechanical structure of the magnet. Corrective actions were taken to counterbalance their effects but no further analysis was performed at the time. Recent developments in hardware and software make this analysis more feasible. In this paper we present the results of the transient magnetodynamic simulation that was set up in order to model these eddy currents and study their impact on the M25/2 field quality.

M25/2 KICKER MAGNET

The M25/2 slow kicker magnet (see fig. 1) located in the first section of the EPB2 is driven by a current pulse with a repetition rate of 10 Hz. The pulse shape is approximately a 28 ms half sine wave with a 2800 A / 600 µs flat top, followed by a period of 71.4 ms where the current is zero (see fig. 2). The beam kick provided during the flat top is 90 mrad [1] [2].

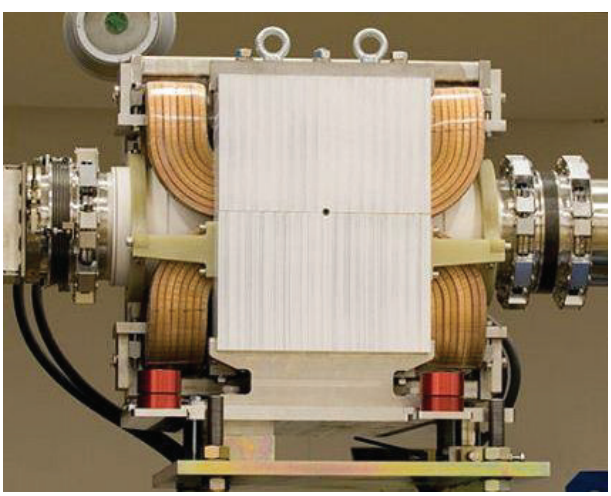

Figure 1: M25 magnet.

The magnet's magnetic core is made of non-grain oriented iron silicon laminations 500 µm thick. The laminations are stacked along the beam axis.

The coils are made of glass cloth insulated hollow copper conductors and are impregnated with an epoxy resin. Both conductors as well as the magnetic core are water cooled during normal operation.

Table 1: M25/2 Parameters

Aperture Size	220 mm
Effective Length	500 mm
Maximum Operating Field	0.95 T
Good Field Region	150 x 140 mm
Field Homogeneity	±0.25 %

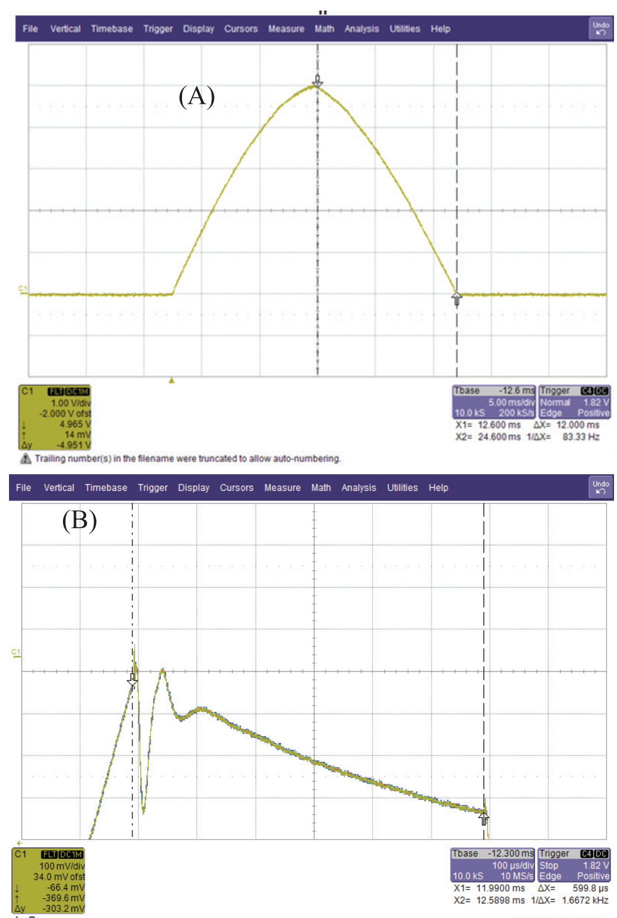

Figure 2: Current pulse (A) and zoom on the compensated flat top (B).

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INITIAL MEASUREMENTS

Measurements were performed using a long rectangular search coil (length: 1255 mm, width: 15.3 mm, 10 turns) inserted inside the magnet. The voltage induced in the coil by the time-dependant flux linkage was digitally integrated using a high precision oscilloscope. NB: for practical reasons certain measurements were performed with the coil centred in the magnet (see fig. 3A); others with the coil inserted halfway (see fig. 3B).

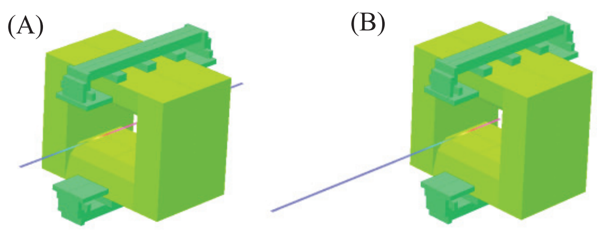

Figure 3: Rectangular patch replicating the coil centred inside the magnet (A). Rectangular patch replicating the coil inserted halfway inside the magnet (B).

When the prototype was measured for the first time, it was noted that the integrated field increased even when the flat top current was held constant (see fig. 4).

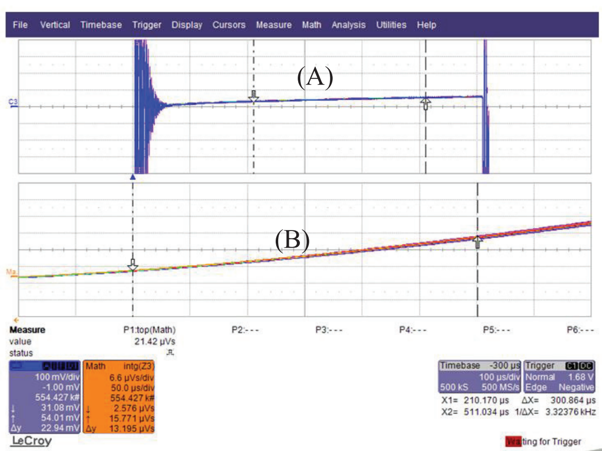

Figure 4: Voltage induced in the search coil (A) and integrated field (B) during the current flat top without current compensation.

In order to counterbalance this instability, it was decided to impose a slight negative rate of change of the current during the 600 μs flat top (i.e.: current compensation – see fig. 5). The requirement in terms of field stability was set to 100 ppm during at least 300 μs when the current flat top is reached.

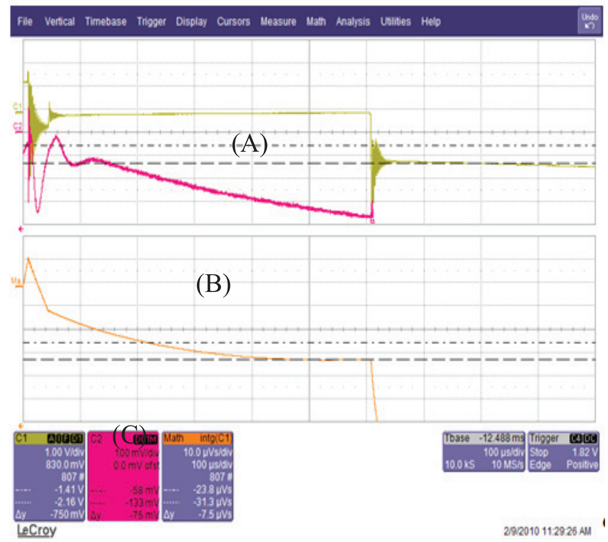

Figure 5: Voltage induced in the fixed coil (A), current (B) and integrated field (C) during the current flat top with current compensation.

PRESENTATION OF THE MODEL

The program OPERA3D [3] was used to perform the simulations. In order to reduce the computation time only an eighth of the complete geometry was modelled. In the regions where eddy currents were expected a hexahedral mesh was used. The mesh density was increased in the regions where the eddy currents are predominant by using graded layers of elements. Tetrahedral elements were used for the rest of the model.

The BH curve of the magnetic core's electrical steel at 50 Hz was used. It was estimated that the core's packing factor was roughly 95 %. To take the effect of the insulation coating of the laminations into consideration an anisotropic permeability and conductivity were selected. The effective permeability in the plane of the lamination (tangential to the lamination) is given by:

$$\mu_t = f\mu_{steel} + (1-f)\mu_0. \quad (1)$$

In the normal direction the effective permeability is given by:

$$\mu_n = \frac{\mu_{steel}\mu_0}{f\mu_0+(1-f)\mu_{steel}}. \quad (2)$$

where f is the packing factor [3].

The structure that supports the coils is made of stainless steel 316L. It was considered as non-magnetic and an isotropic conductivity was used.

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SIMULATION RESULTS VERSUS MEASUREMENTS

Simulation without Current Compensation

A rectangular patch with the same dimensions as the search coil was used to compute the flux linkage. The integrated field normal to the patch was calculated and compared to the flux linked by the search coil.

Without current compensation the calculated integrated field, with the coil inserted half-way (see fig. 3B), increased by 2.98 µVs over a period of 600 µs. The linearized rate of change of the integrated field was 4967 µV (see fig. 6).

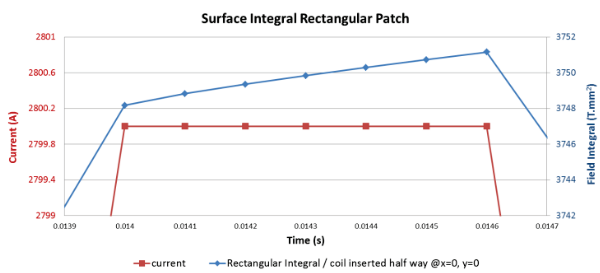

Figure 6: Flux linkage versus current; No current compensation; FEA simulation.

Figure 4 shows that the flux linkage, measured with a 10-turn search coil (inserted halfway inside the magnet) and without the current compensation, changed by 13.195 µVs over a period of 300 µs. The linearized rate of change of the flux linkage per turn was 4398 µV.

The difference between the rate of change of field measured and calculated is 11.4 %.

Simulation with Current Compensation

The same methodology as described previously was used with current compensation (-5600 A/s). The integrated field decreased by 2.29 µVs over a period of 600 µs. The linearized rate of change of the integrated field was -3822 µV (see fig. 7).

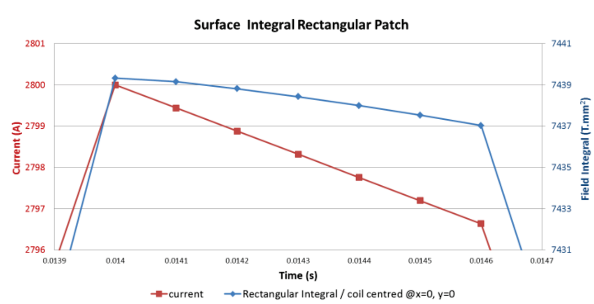

Figure 7: Flux linkage versus current; with current compensation; FEA simulation.

Figure 5 shows that the flux linkage measured with a 10-turn coil (centred inside the magnet) and with a current compensation of approximately 6000 A/s decreased by 14.4 µVs over a period of 480 µs (measured after the current transient). The linearized rate of change of the flux linkage per turn was approximately -3000 µV. The ratio between the rate of change of the current versus the rate of change of the field was 0.5 µVs/A. This is to be compared with the ratio of 0.6825 µVs/A obtained with the FEA simulation (a difference of 26 %).

It is believed that the discrepancies between the results of the simulations and the measurements are mainly due to:

- The use of a BH curve for the iron silicon steel characterised with a 50 Hz sine wave instead of the 10 Hz pulsed signal used to drive the magnet.
- The fact that the hysteretic behaviour of the iron silicon steel was neglected.
- The difference between the real current drive and the one used for the simulation.
- Manufacturing and alignment imperfections.
- Data acquisition and integration errors.

Unfortunately not enough data is currently available to quantify precisely the impact of these discrepancies.

CONCLUSIONS

A transient FEA simulation was set up to analyse the effect of the eddy currents induced in the core and the mechanical structure of the pulsed M25/2 slow kicker magnet installed at ISIS.

A good approximation of the impact of the current drive on the field was obtained. The calculated and measured rate of change of the current versus the rate of change of the integrated field over the flat top period corresponds relatively well (within 26 %).

It is believed that a better representation of the BH curve as well as the hysteretic effects of the iron silicon lamination excited with 10 Hz pulsed waves are needed in order to improve the model.

ISIS is currently investing in a magnet measurement facility. When this facility is up and running, more AC and pulsed magnets will be thoroughly tested and the methodology to model these components will be refined.

REFERENCES

[1] S. L. Birch "TARGET STATION 2 – Factory Acceptance Test for spare 10 Hz Kicker Power Supplies – February 2010".

[2] E.P Quinn and S. L. Birch "TARGET STATION 2 – Technical specification for the detail design, manufacture, supply, testing and delivery of a Pulsed Magnet System for the ISIS Second Target Station Extracted Proton Beamline – December 2005".

[3] Cobham Technical Services "Opera-3d User Guide - version 16R1 –November 2013".