Advanced LIGO ITM/ETM SUS Magnets at Top Mass
LIGO-T050105-00-K

K.A. Strain

June 27, 2005

Introduction and references

It is planned to have magnets for OSEM control and eddy-current damping at the top mass of the ITM and ETM suspensions for Advanced LIGO. The baseline design has ECD magnets on the tablecloth. This document considers requirements related to magnetic interactions internal and external to SUS resulting it two alternative design approaches[1].

Some background is given by Fritschel in G010086; requirements relating to external magnetic interactions are given in E050159 (chapter of E030647). Generic requirements for the suspensions are given in T010007-03.

Every noise evaluation in this paper is carried out at 10 Hz, as there is rapidly increasing isolation above this (with 6th or 8th power of frequency).

The estimated field gradient at the top mass is (from E050159) $< 20\,\mathrm{pTm^{-1}}/\sqrt{\mathrm{Hz}}$, the field being $< 10\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$. These are given for 100 mm below the optics table, approximately 200 mm above the nearest (uppermost) magnet, and so represent upper limits.

The latest MATLAB ITM/ETM model (REF: N.A. Robertson), gives the worst case coupling of force on the top mass to longitudinal displacement on the TM as $5\times10^{-11}\mathrm{m/N}$ at 10 Hz (this is for vertical forces, longitudinal being about 2 times better isolated). The maximum force allowed is therefore $2\times10^{-10}\,\mathrm{N}/\sqrt{\mathrm{Hz}}$ to meet the $10^{-20}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ noise target. In this case, given the uncertainties involved, a large margin should be included. Allowing an extra factor of 10 margin, the largest tolerable dipole moment on the top mass is $1\,\mathrm{Am^2}$.

In the controls prototype design there is a single pitch-control OSEM with about $0.5\,\mathrm{Am^2}$. We propose incorporating an extra magnet oppositely magnetised and placed within about 50 mm of the pitch-control OSEM to mostly cancel the dipole moment. Similar action should be taken for the transverse horizontal OSEM magnet (remembering that the field gradient and hence force could be in any direction). The other 4 OSEM magnets are already in pairs, although these are quite far apart and higher order multipoles are likely to react to fields from the SEI subsystem.

If ECD magnets are to be placed on two faces of the top mass (not the present baseline plan), the residual dipole moment should be no more than about $0.1\,\mathrm{Am^2}$ on each of two faces of the mass.

If ECD magnets are placed on the tablecloth (the baseline) they will interact with the OSEM magnets on the top mass. This will manifest as static forces that may lead to misalignment, and magnetic springs between the tablecloth and mass that may lead to shorting of the isolation or changes in the pendulum dynamics.

[1] Ian Wlimut spotted that there were problems here when looking at the layout of the top mass.

1 Option 1: ECD magnets on the top mass

UK magnet vendor ‘Magnet Developments’ was consulted and confirmed that magnets of the type we require, taken from one batch, could show a spread of approximately 5% for a sample of a few hundred magnets. Additionally, it was suggested that magnets could be graded into 2% matched grades at modest cost (with the benefit that the absolute strength of each grade would be given). It is proposed that this option is taken in any case to provide control of magnet strength.

The shape of the field from the SEI equipment is not known, but a reasonably conservative upper limit to the likely force can be found by estimating the worst case dipole moment from 16 ECD magnets arranged in four closely grouped N, S, N, S facing quadruplets. Because the groups are compact – 14 mm centre-to-centre spacing of 10 mm diameter magnets – the higher order multipoles are negligible when the source of the interacting fields is more than 300 mm distant. With magnets from a 2% grade the worst case would be to have 8 strong and 8 weak magnets in the worst combination. This would give a residual dipole of 16% of one magnet or 0.08 Am^2. Most combinations of magnets would be much better and the additional dipole moment would be very unlikely to exceed that already present from the OSEM magnets. Thus fitting all magnets to the mass becomes a valid option.

(This is no real surprise as very similar magnets are allowed, widely spaced, for global control on the upper-intermediate mass.)

2 Option 2: ECD magnets on the tablecloth

To avoid unwanted alignment offsets, the force between magnets on the tablecloth and magnets on the mass should not exceed about 1 mN per OSEM magnet (thus in the worst case not requiring more than 10% of the OSEM bias range to compensate). The interaction of 2 dipoles was investigated in some detail (following the general methods given by Barton in a Mathematica notebook). It is not necessary to consider higher multipoles of the ECD magnet fields, provided the OSEM magnets are on the appropriate lines of symmetry (nearest two magnets are opposed) and the distance to the OSEM magnet is large compared to the 14 mm spacing of ECD magnets. It is best to have a symmetrical layout is so that ECD units are all spaced by the same distance from the nearest OSEM magnets. The alignment of the mass is quite well constrained (it can only move 1 mm in any direction – much less than the spacing of the magnets), so these assumptions are applicable to any possible alignment. Note that very crude estimates and measurements of the magnetic forces in pick-up tests (see appendix), give nearly the same result as the more complex calculation.

The residual dipole moment of the ECD units is taken to be 0.1 Am^2. The OSEM magnet has a dipole moment of 0.5 Am^2, any compensating OSEM magnet is neglected to obtain a worst case result. The interaction force is, at worst about 1 to 2 mN at a separation of 60 mm (center of OSEM magnet to centreline of nearest pair of ECD magnets). The precise figure depends on whether the magnets are in the same plane, or in a different plane by up to 20 mm (beyond which the force falls monotonically).

The gradients of the force are not more than about 0.03 N/m provided the magnets are spaced by more than 60 mm. This should not adversely affect the suspension where the spring constant is of order 1 kN/m.

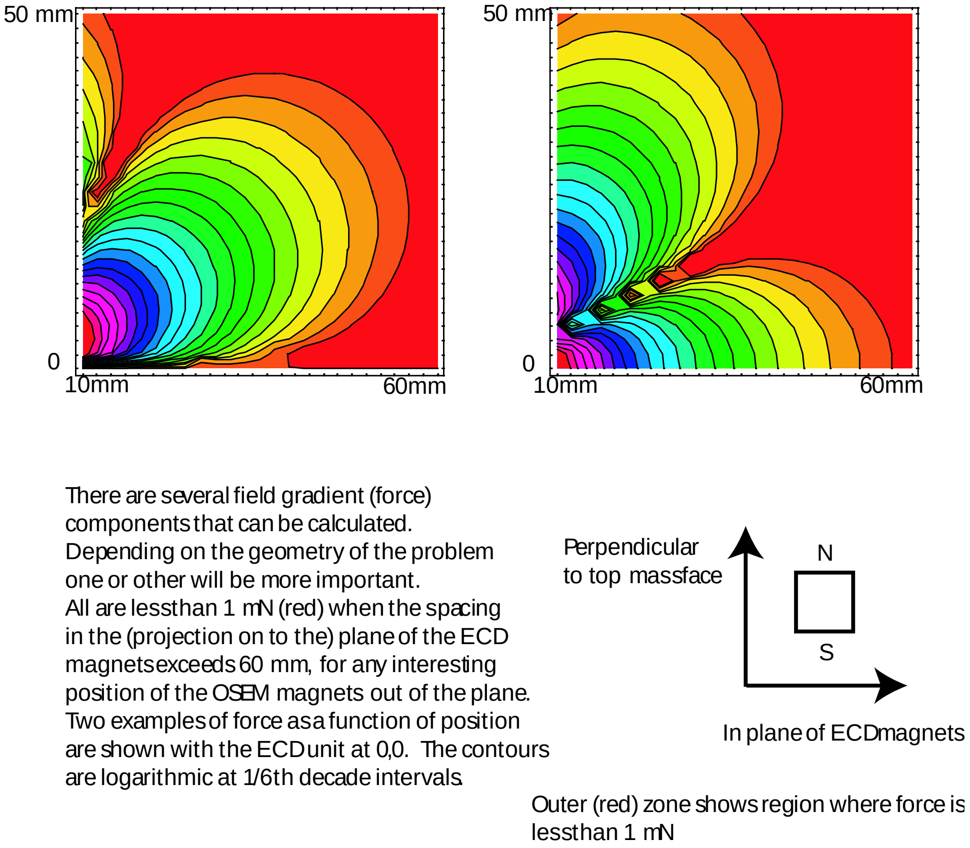

Figure 1: Examples of force (field gradient times dipole moment) produced between ECD and OSEM magnets.

3 Conclusions

Some minor design changes are needed to reduce the residual dipole moment from the OSEM magnets on the top mass of the ITM/ETM suspensions.

Adding the ECD, especially if graded magnets are employed, should not add significantly to the forces arising from stray fields.

The baseline plan is still preferable, provided there is a reasonable solution to all of the constraints that apply to the positioning of OSEM and ECD units, including the necessary adjustability.

4 Appendix: estimating magnet strength

Magnet strength, for the sole purpose of estimating forces in the mN range for magnets spaced by a few cm was obtained using pick-up tests. This was done with both co-axially aligned and parallel spaced magnets. The 10 mm diameter 10 mm long magnets produced a force equal to the weight (57mN) of one magnet when separated by 50 mm (centre to centre, axially) and separated by about 40 mm (centre to centre) radially. The corresponding dipole moment is about 0.5 Am^2. It is not recommended that this figure be used for other calculations where the field closer to the magnet is important. Magnets of the same diameter and 5 mm long were found to have about half of the dipole moment.

To provide very crude upper limits, consideration of the on-axis field of a dipole suffices: the field is

$$Ba = m1\ \mu_0/(2\pi(r^2 + z^2)^{3/2})$$

and the force is $m2$ times the gradient of the field, where $m1$ and $m2$ are the dipole moments of the two magnets.

For reference the magnetic material (NeFeB) has a typical density $7500 \pm 100\,\mathrm{kg/m^3}$.