B R O O K H A V E N   N A T I O N A L   L A B O R A T O R Y

MAGNET DIVISION NOTES

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Introduction

In this note we compare the magnetic performance of the first SSC 50 mm dipole magnet DSA207 with what was expected from the calculations. The low field harmonics, the iron saturation effects on the field harmonics and the quench performance will be discussed. The magnet uses the W6733C[1,2] cross section. We shall also briefly discuss the low field harmonics in the another 50 mm aperture short magnet DSA208.

Low Field Harmonics

In this section we shall compute the expected low field harmonics by including various effects which change them. These effects are cumulative and they are counted one by one in the rows of Table 1.

Originally the magnet was designed[1] for zero low field harmonics except for a built in b_8 intended for centering. The coil cross section, referred to as W6733, had the right amount of b_2 (-0.28) and b_4 (0.01) to cancel the harmonics created by non-circular iron aperture (pole notch and vertical face at the midplane). The first row in Table 1 gives the harmonics of the W6733 coil in a circular aperture. However, the specifications for the cable were changed by a small amount[2]. The second row gives the harmonics for this new cable in the cross section called W6733C. Note that the harmonics b_2, b_4 and b_6 also become non-zero.

In the third row the effects of non-circular aperture on the field harmonics are included. As mentioned above, there is a a notch at the pole and a vertical face at the midplane.

The mechanical design of the original collared coil (W6733) included a 30 mil shim at the pole, both in the inner and in the outer layer of the coil. A variation in the size of the pole shim absorbs the variation in the size of the actual coil made for a particular

magnet. Since the thickness of the cable used in the outer layer was reduced by 0.4 mil in W6733C, the effective size of the design pole shim in the outer layer increases by 10.4 mil, thus effectively making it a 40 mil design shim. The actual shim used in DSA207 is 30 mil in the inner layer and 38 mil in the outer layer. Therefore, the pole angle of the coil in DSA207 was as per design in the inner layer but was 2 mil larger in the outer layer. The fourth row of the Table includes the effect of this change in pole angle.

As discussed in reference 3, the permeability of the stainless steel collar is not 1.000 as assumed in the original calculations. The fifth row of the Table 1 lists the harmonics and transfer function for a collar material having a permeability of 1.0025.

In magnetic calculations we used warm dimensions of the iron and coil. However, when the magnet cools down there is a shrinkage in various dimensions. The cold dimensions are computed using the following numbers[3] for shrinkage in going from 300° kelvin to 4° kelvin:

Yoke : 2.1 mil/inch

Collar : 2.6 mil/inch

The warm iron inner diameter of 5.339″ becomes 5.328″. The cold coil dimensions follow the cold collar dimensions[3]. The new radii of the inner and outer layer are computed using the value for the collar shrinkage. In addition, the cool down is also likely to cause some elliptical deformation in the collar and therefore in the coil. However, in the absence of any calculation (to our knowledge) for estimating the size of this effect, we could not incorporate this ellipticity in our calculations. Without any change in ellipticity, the shrinkage would mainly change the transfer function; the change in field harmonics would be minimal. In row number 6, such a calculation is included.

Finally, 3 mil shims were used between the collar and the yoke at the top and bottom part of the collar near the pole notch. This was something particular to the magnet DSA207 only. These shims deform the collar which in turn deforms the coil. We assume an elliptical deformation of the coil to compute these effects. These computations are model dependent and the calculations may not be so reliable. However, please note the comment below for row 10 where the measurements for DSA207 is compared with DSA208.

In the next two rows of the table, we list the measurements for DSA207. We have taken the average of the up and down ramp at I=2 kA to obtain the cold geometric multipoles and the average of I=+10 A and I=-10 A to obtain the warm geometric multipole.

In the last row we present the measured cold geometric multipole the DSA208. Unlike in DSA207, DSA208 does not have any shim between the collar and the yoke of this magnet. Therefore, by comparing the measurements between DSA207 and DSA208, one can evaluate the reliability of the shim calculations for this particular case. The agreement appears to be good.

Table 1: Expected and Measured Low Field Harmonics and the Transfer Function in the SSC 50 mm short magnets **DSA207** and DSA208. Measurements in DSA208 should be compared with the calculations in the row number 6.

		T.F. T/kA	b_2' 10^{-4}	b_4' 10^{-4}	b_6' 10^{-4}	b_8' 10^{-4}	b_{10}' 10^{-4}
1	W6733 Original Coil	1.0452	-0.28	0.01	-0.00	0.04	0.01
2	W6733C Coil	1.0477	1.29	0.08	-0.02	0.04	0.01
3	+ non-circular aperture	1.0474	1.57	-0.02	-0.02	0.04	0.01
4	+ Pole Shims	1.0470	1.15	-0.02	-0.02	0.04	0.01
5	+ $\mu = 1.0025$ Collar	1.0478	0.56	0.05	-0.01	0.04	0.01
6	+ Effect of cool down	1.0503	0.66	0.04	-0.01	0.04	0.01
7	+ Collar-Yoke Shims	1.0501	0.36	0.02	-0.01	0.04	0.01
8	Measured COLD DSA207	1.0510	1.62	0.37	-0.02	0.04	0.01
9	Measured WARM DSA207	≈ 1.045	1.16	0.47	-0.02	0.04	0.01
10	Measured COLD DSA208	1.0508	1.92	0.42	-0.02	0.04	0.01

Iron Saturation Effects

In fig 1, we have plotted the calculations and measurements for the variation of b_2 with current starting from 2 kAmp. To remove the persistent current effects we take the average of the up and down ramp in the measurements. We force all curves to start from zero to remove the offsets coming out of various reasons. It makes it easy to compare the calculations and measurements. In Fig 1, $CALC$ refers to the results of calculations with the computer code POISSON and MSR to the measurements. We have also done a similar comparison for b_4 in the same figure. These results are also presented in Table 2.

Quench Performance

In this section we compare the short sample predictions and the measured quench plateau. The calculations are somewhat dependent on the formalism and on the method used for interpolation/extrapolation of the measured short sample data. The G. Morgan program AUTOIC89 has been used for calculations during design. A modified version of this program will be used for comparison.

We have done similar calculations using the Sampson's formula[4] which contains a simple extrapolation of the measured short sample performance of the cable. For the inner layer of the SSC 50 mm magnet the formula is

$$I_{ss} = 7350 + 1100 \left(4.3 - T\right) + 0.17 \left(I_{ss}^{7T} - 10140\right),$$
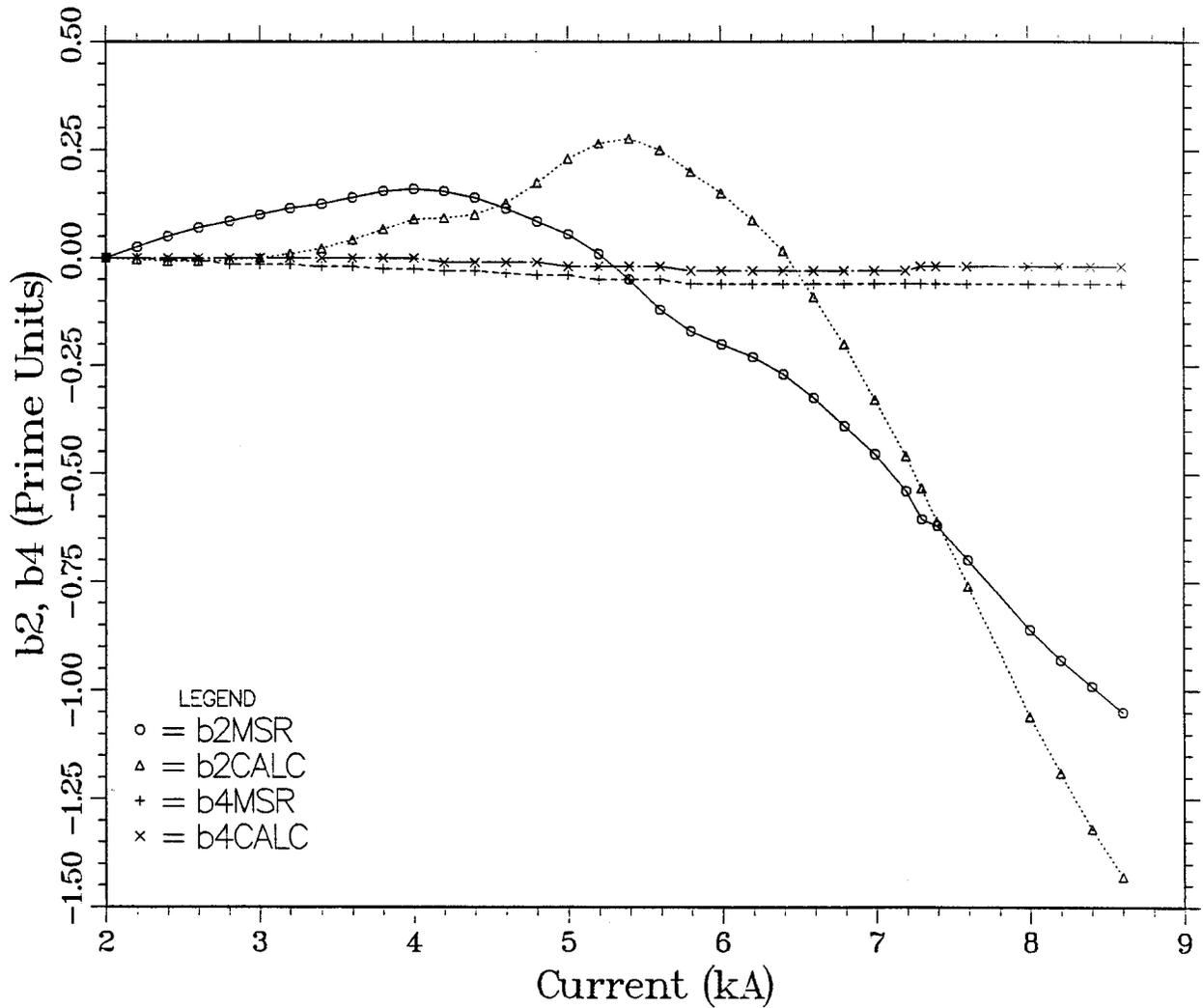
where I_{ss}^{7T} is the measured short sample at 7 tesla and 4.22° kelvin and T is the temperature at which the calculations for the short sample current (I_{ss}) are to be made.

The cable used in magnet DSA207 has a critical current (I_{ss}^{7T}) of 10827 ampere measured at 7 tesla and 4.22° kelvin. We have used this value of I_{ss}^{7T} in calculations.

At very high field, where no measurements are available, the Green's formalism[5] may be more useful. For comparison purpose, we did these calculations in all cases using the the Green's formalism. Morgan's new program AUTOIC90 switches over to Green's method when the peak field in the conductor is slightly above 8 tesla. In the present case, it occurs at a temperature of about 3.77° kelvin.

In Table 3, we compare the calculations for the computed quench current and observed plateau for quench current in DSA207 at various operating temperature. The magnet

Figure 1: Comparison of the calculations and measurements for the iron saturation effects on the sextupole and decapole harmonics in DSA207. We force all curves to start from zero at 2 kA by introducing a proper offset.

Table 2: Computed and Measured variation in the Field Harmonics as a function of current in the first SSC 50 mm short magnet **DSA207**.

I(kA)	Measured b_2	Computed b_2	Measured b_4	Computed b_4
2.0	0.0	0.0	0.0	0.0
2.2	0.025	-0.004	0.	0.0
2.4	0.05	-0.007	-0.005	0.0
2.6	0.07	-0.007	-0.005	0.0
2.8	0.085	-0.005	-0.015	0.0
3.0	0.1	0.	-0.015	0.0
3.2	0.115	0.009	-0.015	0.0
3.4	0.125	0.022	-0.02	0.0
3.6	0.14	0.042	-0.02	0.0
3.8	0.155	0.067	-0.025	0.0
4.0	0.16	0.09	-0.025	0.0
4.2	0.155	0.093	-0.03	-0.01
4.4	0.14	0.101	-0.03	-0.01
4.6	0.115	0.127	-0.035	-0.01
4.8	0.085	0.174	-0.04	-0.01
5.0	0.055	0.23	-0.04	-0.02
5.2	0.01	0.265	-0.05	-0.02
5.4	-0.05	0.276	-0.05	-0.02
5.6	-0.12	0.25	-0.05	-0.02
5.8	-0.17	0.199	-0.06	-0.03
6.0	-0.2	0.15	-0.06	-0.03
6.2	-0.23	0.088	-0.06	-0.03
6.4	-0.27	0.016	-0.06	-0.03
6.6	-0.325	-0.09	-0.06	-0.03
6.8	-0.39	-0.2	-0.06	-0.03
7.0	-0.455	-0.33	-0.06	-0.03
7.2	-0.54	-0.46	-0.06	-0.03
7.3	-0.605	-0.534	-0.06	-0.02
7.4	-0.62	-0.61	-0.06	-0.02
7.6	-0.7	-0.76	-0.06	-0.02
8.0	-0.86	-1.06	-0.06	-0.02
8.2	-0.93	-1.19	-0.06	-0.02
8.4	-0.99	-1.32	-0.06	-0.02
8.6	-1.05	-1.43	-0.06	-0.02

behaved very well and all normal quenches were above the plateau value listed in Table 3. The quench performance of this cross section is limited by the inner layer. The outer layer has about 2.5% higher quench field and therefore, as expected, no quench was seen originating in the outer layer. For this reason the comparison between the calculations and measurements can only be made in the inner layer.

Table 3: The computed quench current and the observed plateau for quench current in the SSC 50 mm magnet **DSA207.**

Temperature →	4.35° K	3.85° K	3.35° K
Computed	7440 A	7896 A	8578 A
Observed	7500 A	8100 A	8700 A

As mentioned earlier the computed values in Table 3 are based on Morgan's current program AUTOIC90. At 4.35° kelvin it predicts 7440 ampere which is 0.8% lower than the observed 7500 ampere. Sampson's formula gives 7412 ampere (1.2% lower) and Green's gives 7422 ampere (1.1% lower). Note that there is a 0.4% spread in the predicted values from various formalism. At 3.85° kelvin Morgan's formalism gives 7896 ampere which is 2.6% lower than the observed 8100 ampere. Sampson's formula gives 7962 ampere (1.7% lower) and Green's gives 8048 ampere (0.7% lower). Note that there is a 1.9% spread in various formalism. At 3.35° kelvin the program AUTOIC90 uses the Green's formalism. The predicted value is 8578 ampere which is 1.4% lower than the observed 7500 ampere. Sampson's formula gives 8512 ampere (2.2% lower). Note that there is a 0.5% spread in the two formalism.

References

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