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## RECENT TEST RESULTS OF THE FAST-PULSED 4 T COS $\theta$ DIPOLE GSI 001

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### Abstract

For the FAIR-project at GSI a model dipole was built at BNL with the nominal field of 4 T and a nominal ramp rate of 1 T/s. The magnet design was similar to the RHIC dipole, with some changes for loss reduction and better cooling. The magnet was already successfully tested in a vertical cryostat, with good training behaviour. Cryogenic losses were measured and first results of field harmonics were published. However, for a better understanding of the cooling process, quench currents at several ramp rates were investigated. Detailed measurements of the field harmonics at 2 T/s between 0 and 4 T were performed.

### INTRODUCTION

Gesellschaft für Schwerionenforschung (GSI) is planning to build FAIR ( Facility for Antiproton and Ion Research), as a major upgrade of its existing facility in Darmstadt, Germany (see GSI website [www.gsi.de](http://www.gsi.de)).

The SIS 200 synchrotron ring design has been changed, from dipoles with 80 mm coil aperture, 4 T central field, with a challenging ramp rate of 1 T/s, to SIS 300, having dipoles with 100 mm coil aperture, 6 T central field, ramp rate remaining unchanged. A reduction of magnet energy losses during ramping, as well as the effect of fast ramping on magnet field quality are therefore two areas that required work. The R&D that began in 2001 for the SIS 200 dipoles, to develop a low loss, fast-ramping accelerator dipole, has provided valuable information that is also relevant for the SIS 300 dipoles.

The SIS200 1 m long model dipole GSI001 (see Figure 1), based on the RHIC dipole design but incorporating a number of loss reduction features, was built and tested by BNL [1,2,3]. For loss reduction, it has a Rutherford cable with a stainless steel core, 4 mm filament twist pitch (versus 13mm in RHIC), low coercivity yoke iron, and non-metallic coil wedges. The Kapton coil insulation has holes at the inner edge, giving a 26% open area, for better cooling. Initial results have been obtained for the GSI001 field harmonics during rapid ramping, using a new BNL developed measurement system [4].

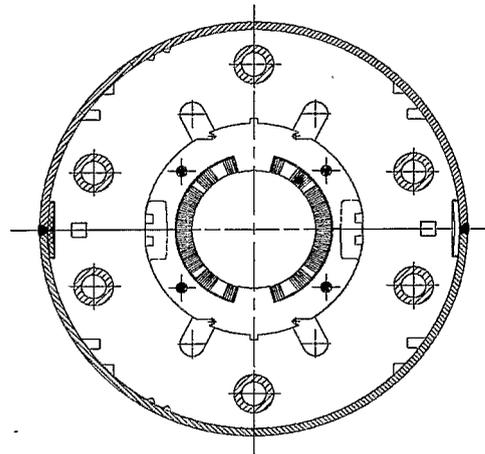


Figure 1: Cross section of the magnet.

### RAMP RATE EFFECTS

The cold mass was tested in a vertical liquid helium Dewar with boiling liquid helium. For training, the magnet was initially ramped at 0.53T/s[1]. Ramp rate limitation was then measured by ramping at faster rates for many cycles until thermal equilibrium was reached and then increasing the maximum current until a quench occurred; Figure 2 shows the results.

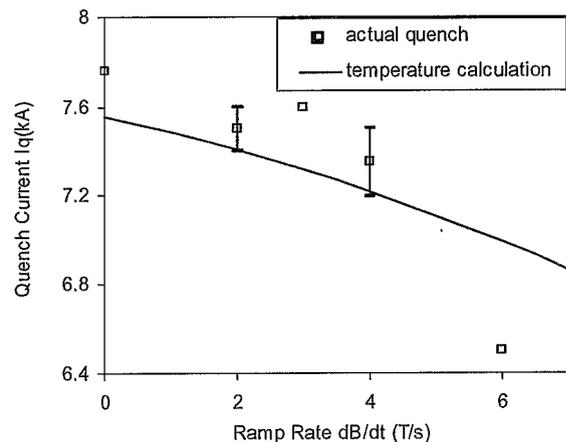


Figure 2: GSI 001 quench current  $I_q$  versus ramp rate dB/dt.

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One can see that the quench current exhibits “type A” behaviour [5], i.e.  $I_q$  is primarily determined by conductor AC-heating (eddy and persistent current effects). The quench current degradation is rather small due to the moderate heating and good cooling of the conductor.

The temperature rise in the high field region of the conductor was estimated for several different ramp rates and from this the reduction in critical current due to heating was calculated (see Figure 2). Initially, the measured and calculated values track each other reasonably well, although at 6 T/s this is no longer the case. The critical current was calculated with an estimated 6% current degradation due to cabling. This may be pessimistic.

### MAGNET LOSSES

AC losses during ramping have been measured by an electrical method and calculated using properties of the wire and cable measured on short samples [1] and [2].

While theory and experiment agreed quite well for the hysteresis loss (intercept in Figure 3), the agreement for the eddy current loss (slope in Figure 3) was not so good.

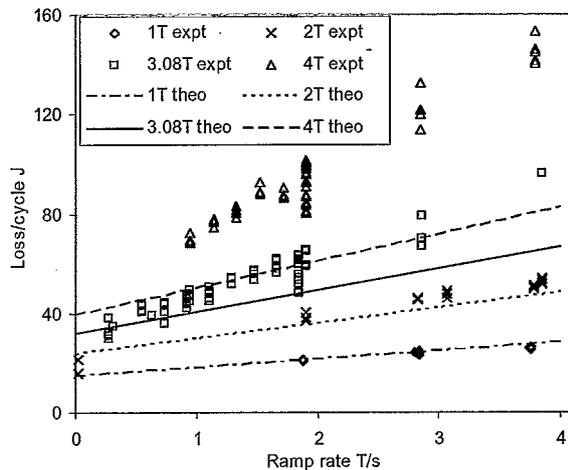


Figure 3: Losses per cycle versus dB/dt.

The eddy current losses were higher than calculated, especially at high fields, when the iron started to saturate (up to 60 J/cycle at 4 T, 4 T/s). We calculated the potential eddy current contributions by end field effects, by the collars, by brass spacers in the magnet lead end, by the rods, which hold the iron laminations – the total of these contributions was about 2 J/cycle at 2 T/s. Only the contribution from eddy currents in the helium containment shell was appreciable – some 6-7 J/cycle at 4T, 4 T/s.

In order to solve the puzzle we reduced the cold mass to the collared coil only (with a G10 and SS support structure) and tested it in a vertical Dewar. However, lacking the laminated iron shield, the loss contribution by the low carbon iron of the cryostat's vacuum vessel was substantial. Therefore, a specific answer was not possible.

### 2D FIELD QUALITY

Of course, beam dynamics people worry about the field quality of a fast-ramped superconducting accelerator magnet. Using the new BNL measuring system [4] the main harmonics  $b_3$  and  $b_5$  were determined at DC and at 2 T/s. The codes VF Opera 2D and ROXIE [6] were modified to calculate the persistent and eddy current effects. Both codes take into account the persistent current and interfilament coupling effects including magnetoresistance. In Opera 2D some preliminary estimates of the interstrand coupling terms were made [7] [8], but these results are tentative and not included in the following plots.

Figure 4 presents the sextupole term  $b_3$  at 2T/s (in relative units @ 25 mm radius), as measured and as computed by ROXIE, showing the excellent agreement between the two. The geometrical harmonics are high and saturation starts already at 3000 A. It must be pointed out that this experimental magnet was built to demonstrate the feasibility of fast ramping. Existing components were used to save time and money, therefore the magnet was not at all optimized for geometric field quality.

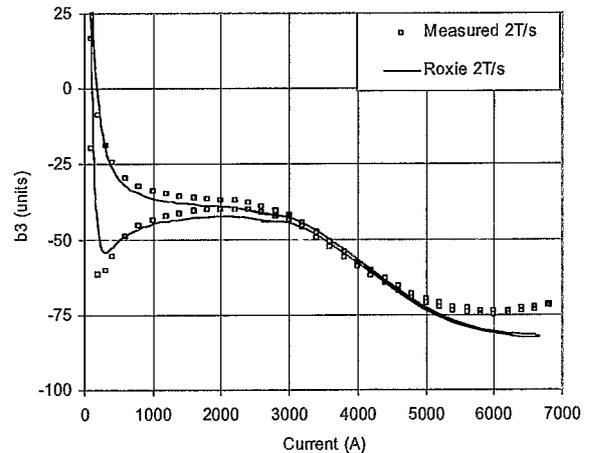


Figure 4: Measured sextupole field (in units of  $10^{-4}$  @ 25 mm radius)

In an accelerator magnet the coil and iron geometry will of course be optimized to produce a good field quality, but errors coming from the superconductor will remain as an irreducible minimum. To estimate these errors we use the fact that harmonic terms from the superconductor are reversed when ramping up or down. Computer calculations show that the difference between up and down due to iron hysteresis is negligible. Thus the superconducting component of each harmonic is simply given by half the difference between ramping up and down. Each of these harmonic terms comprises a DC component coming from persistent currents and a term proportional to ramp rate, which comes from the coupling currents between filaments in the wires and between wires in the cable.

Figure 5 shows the sextupole component at DC and 2T/s. A further simulation using Opera seems to show that interstrand coupling currents reduce the harmonic terms slightly (less than one unit). From Figure 5, one sees:

- The persistent current effect is  $\approx 4$  units at the synchrotron 'stretcher mode' injection field of 0.5 T (800 A) and  $\approx 1.4$  units at the pulsed mode injection field of 1.5 T (2400 A).
- The AC effect at 2 T/s is smaller than the DC-value, about 2 unit at the lowest injection field
- The two codes agree with each other and describe the experimental data quite well.

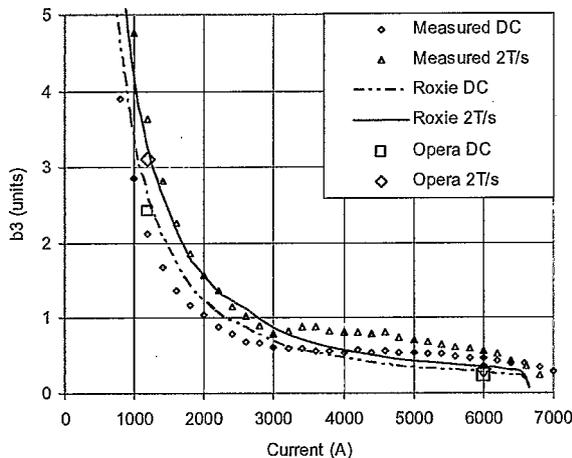


Figure 5: Sextupole term coming from the superconductor (in units of  $10^{-4}$  @ 25 mm radius)

The decapole term shown in Figure 6 is much less than the sextupole under DC conditions, but gets much larger when ramping. This behaviour is completely at variance with the computer simulations, which predict a very small effect from coupling currents. At present we have no explanation for this discrepancy.

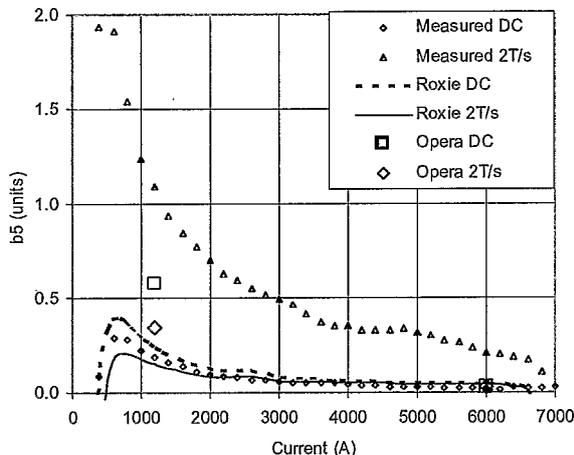


Figure 6: Decapole term coming from the superconductor (in units of  $10^{-4}$  @ 25 mm radius)

## SUMMARY

The purpose of this work was to investigate the influence of persistent and coupling current effects on the quench behaviour, the cryogenic losses, and the field quality of the fast-pulsed accelerator dipole GSI001.

The main conclusion is that such a magnet can be used in a synchrotron. Quench behaviour is dominated by Joule heating, cryogenic losses are tolerable and the AC field quality is acceptable. The theory describes the measured data quite well, so the results can be transferred to other magnets of a similar type. However, some eddy current losses – most probably in the structure – still remain undiscovered and need further investigation.

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