Superconducting Magnet Division

Magnet Note

Author: A. Jain, G. Ganetis, P. Joshi, W. Louie, A. Marone, R. Thomas, P. Wanderer

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Topic: Magnet Measuring Results and Techniques

Title: Measurements of Field Quality in GSI001 at High Ramp Rates

M. Anerella
J. Cozzolino
J. Escallier
G. Ganetis
M. Garber
A. Ghosh
R. Gupta
H. Hahn
M. Harrison
J. Herrera
A. Jain
P. Joshi
W. Louie
J. Muratore
S. Ozaki
B. Parker
S. Peggs
F. Pilat
S. Plate
C. Porretto
W. Sampson
J. Schmalzle
J. Sondericker
S. Tepikian
R. Thomas
D. Trbojevic
P. Wanderer
J. Wei
E. Willen

Measurements of Field Quality in GSI001 at High Ramp Rates

Animesh Jain, George Ganetis, Piyush Joshi, Wing Louie, Andrew Marone,
Richard Thomas, and Peter Wanderer

Superconducting Magnet Division
Brookhaven National Laboratory, Upton, NY 11973-5000

1. Introduction:

The prototype magnet designed for fast-ramp operation, GSI001, was cold tested in November 2005 after the yoke was reattached to the collared coil. These tests were conducted in a stainless steel dewar in order to minimize the influence of eddy currents in the dewar walls when the magnet is operated at high fields and the yoke is highly saturated.

Apart from energy loss measurements, field quality was also measured during these tests. The field quality measurements were made at nominal ramp rates (dB/dt) of 1.5, 2.0, 3.0 and 4.0 T/s (corresponding to current variations, dI/dt, of 2.4, 3.2, 5.0 and 6.9 kA/s). The current cycle used for all ramp rates was from 100 A to 7000 A and back. Several improvements were made during the November 2005 run to improve the accuracy of the measured harmonics.

This note gives a very brief description of the measurements and summarizes the results obtained.

2. Measurement System:

The measurements were carried out using the 16-coil non-rotating probe built for measurements at fast ramp rates. In order to improve the resolution of the measurements, the coil signals were acquired in this run using sixteen HP3458A voltmeters instead of 16-bit ADCs used in earlier measurements. A 17^{th} HP3458A meter was used to record the current. Even with a typical voltmeter aperture of 1 ms used in these measurements, the HP3458A voltmeters have an effective resolution of about 21 bits (6.5 digits).

Another drawback of earlier measurements at high ramp rates was the availability of only 16 signals. As a result, only a few lower order terms could be obtained. In particular, it was not possible to calculate the magnetic center of the dipole and correct the data for feed down. The analysis was also prone to errors due to aliasing.

In order to overcome the limitation of poor angular resolution, a scheme of combining data from two separate runs was implemented during the November 2005 run. In this scheme, data were first acquired with the probe positioned in its "natural" orientation (as defined by the index pulse from the angular encoder). The probe was then rotated by 11.25 degrees (half of angular separation between two adjacent coils) and another set of measurements was made. Combining these two sets of measurements, one obtains the angular dependence at 32 points instead of only 16. This nearly eliminates the aliasing problem, and allows computation of higher order harmonics, which, in turn, can be used also for centering corrections. The analysis of the data is carried out in such a way that the ramps, as well as the triggers for the data acquisition, need not be matched perfectly during the runs at the two probe orientations.

3. Ramp Cycles Used:

All ramps were carried out from 100 A to 7000 A and back. Starting at 100 A, the ramp rate was increased linearly with time (i.e., the current varied quadratically with time) from zero to the maximum value. The ramp rate was then held constant (i.e., the current varied linearly with time) and then reduced to zero linearly with time (i.e. the current varied quadratically with time again) in such a way that the current reached the maximum value of 7000 A when the ramp rate reached zero. The parameters of the acceleration and deceleration phases were chosen in such a way that the acceleration and deceleration times were each equal to 10% of the total ramp time. It should be noted that the ramps implemented were for constant dI/dt, and not constant dB/dt.

One measurement "set" consisted of data taken during four successive up and down cycles between 100 A and 7000 A at the chosen ramp rate. At each ramp rate, there were 6 such "sets" of measurements made - three "sets" with one orientation of the measuring coil, and then three "sets" with the measuring coil rotated by 11.25 degrees.

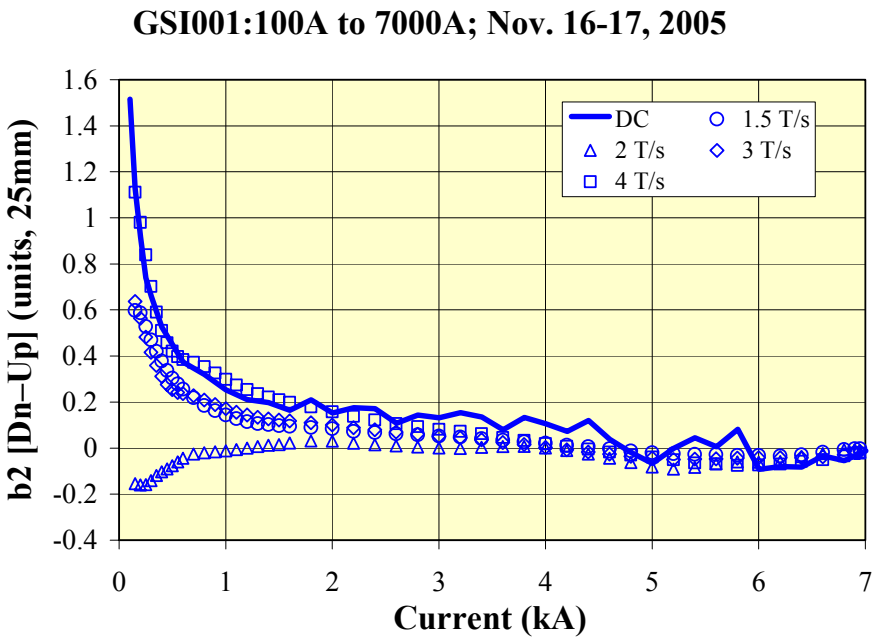
4. Data Analysis and Results:

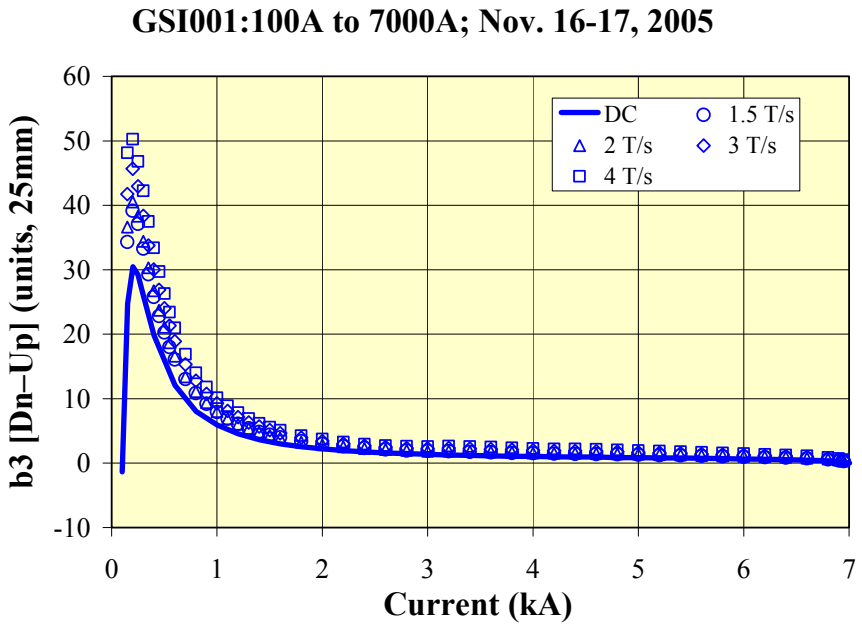
The raw voltage signals were integrated numerically to obtain the change in flux at any instant relative to the initial value. The initial flux was computed using field harmonics measured at 100 A using the probe in a rotating mode just before starting the ramps. The flux values are susceptible to drift due to any small offsets (typically ~10-100 μV) in the voltage measurements. All the flux values were corrected for drift by comparing the integrated voltages at fixed currents in the up and down ramps of the four successive ramp cycles of the same "set".

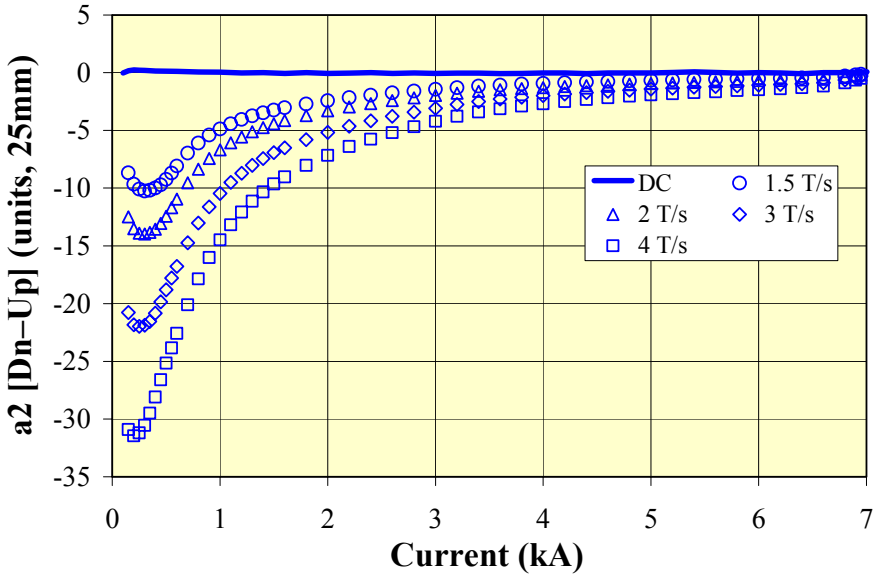
In principle, two "sets" of measurements – one at each angular position of the probe, are sufficient to obtain all the harmonics of interest. In practice, it was found that the data quality is significantly affected by 60 Hz (or multiples of 60 Hz) noise. To minimize the impact of such noise, all the six "sets" acquired at a given ramp rate were included in a single analysis to obtain the field harmonics. This effectively allowed an averaging of flux information at each of the 32 angular positions, resulting in a much better cycle-to-cycle reproducibility. It should be stressed here that the analysis makes use of integrated voltages that are interpolated at fixed values of currents. This approach significantly relaxes the requirement that all the ramps and triggers be perfectly matched in all the "sets".

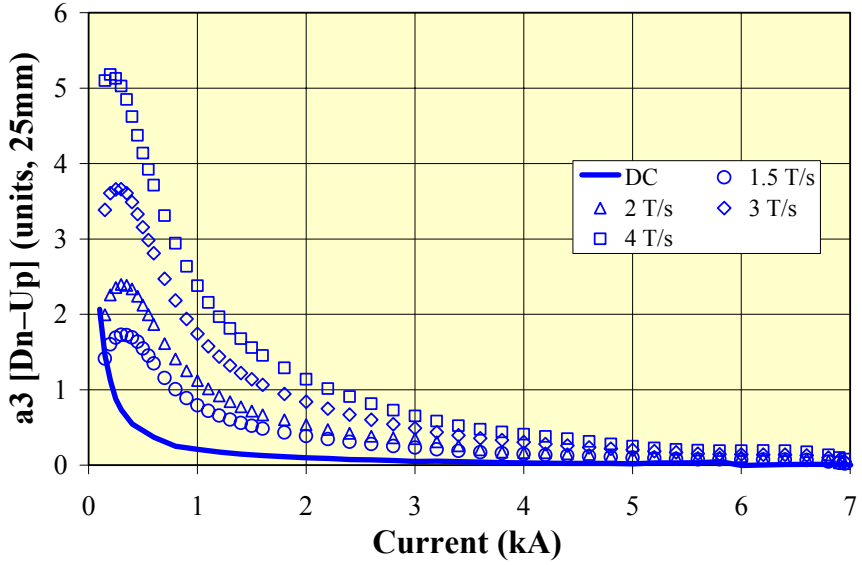
The analysis of the angular profile was performed to obtain the field harmonics up to 26-pole ($n = 13$). The field harmonics were used to compute the centering parameters (22-pole to 20-pole feed down), and then center and rotate the data to obtain results in a reference frame aligned to the magnet. The harmonics are computed at each of the interpolation currents (typically chosen to be every 50 A) for both the up and the down ramps in each of the four ramp cycles. Only harmonics up to 22-pole ($n = 11$) appeared to be reliable.

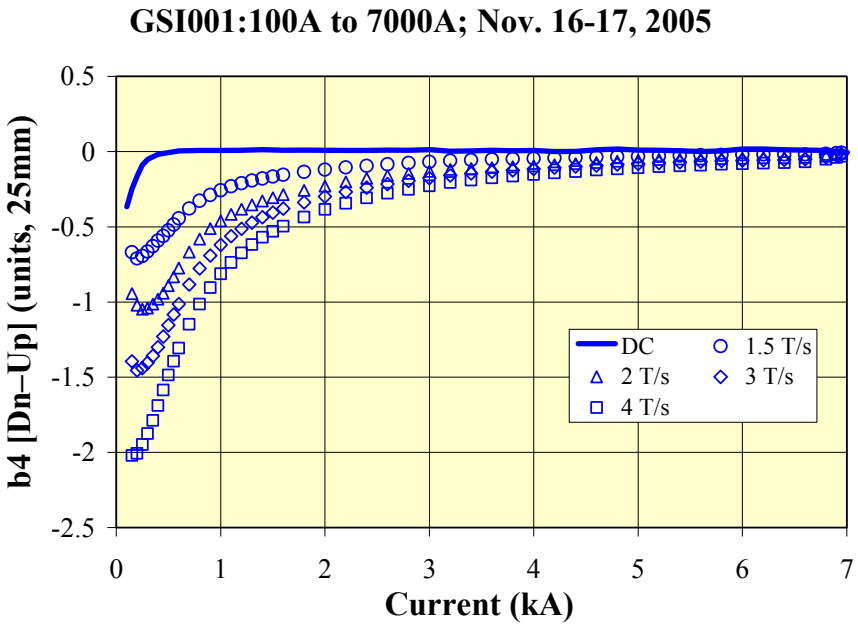
The effect of ramp rates is most clearly seen in the hysteresis (down ramp to up ramp difference) in various field harmonics. The hysteresis was computed for each cycle, which then provides a mean and standard deviation. The standard deviation is generally well below 1 unit, and is ~0.1 unit for most harmonics above ~1 kA. The hysteresis is shown on p. 3-7 in units, and on p. 8-12 in Tesla. The ramp rate dependence at a fixed current of 1 kA (0.62 T) is shown on p. 13-17. One striking result is the rather large ramp rate dependence in the unallowed skew terms, which may arise, for example, if the interstrand resistances are not the same for the upper and the lower coils in the magnet.

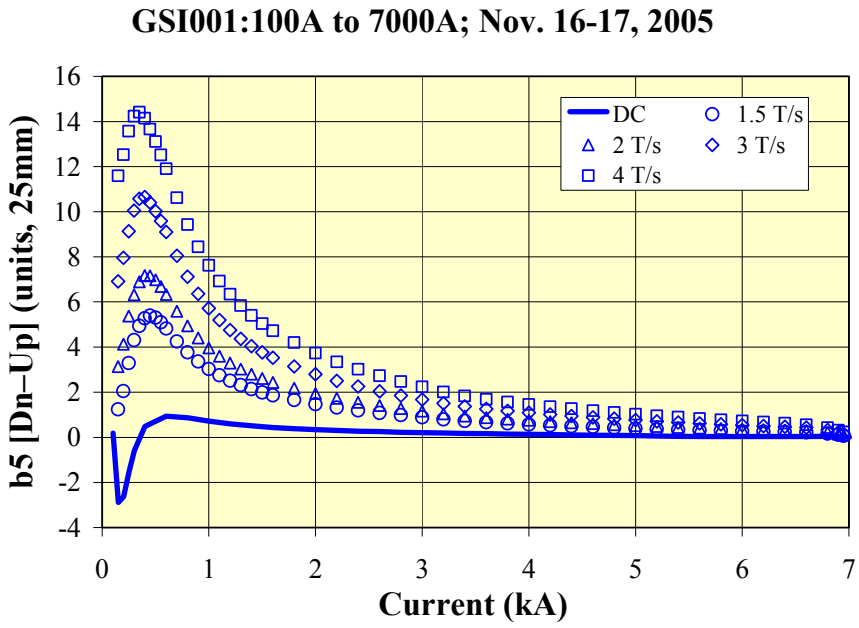

GSI001:100A to 7000A; Nov. 16-17, 2005
b2 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

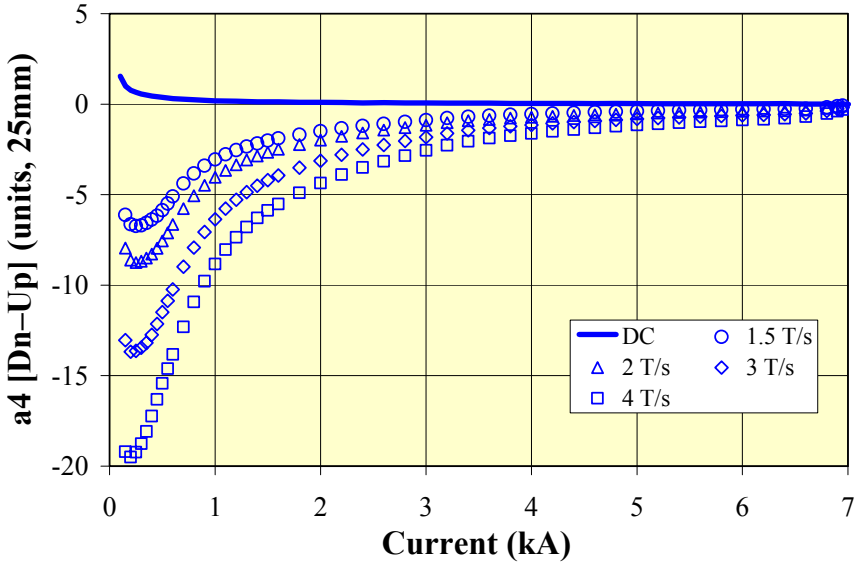

GSI001:100A to 7000A; Nov. 16-17, 2005
b3 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

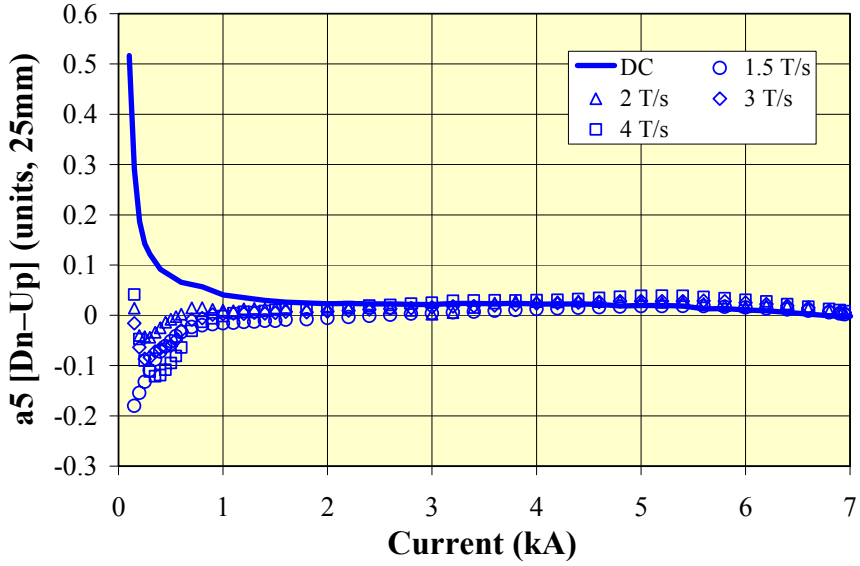

a2 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

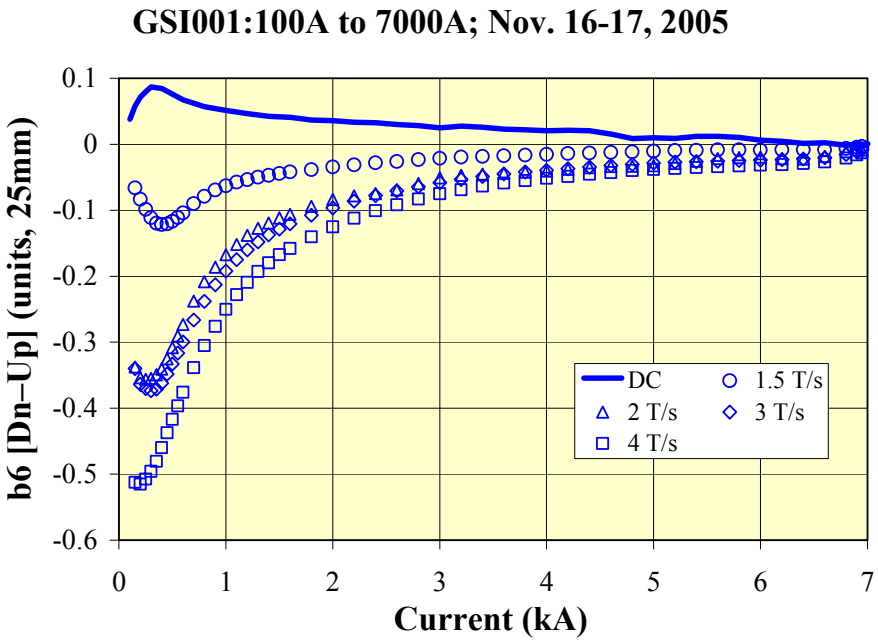

a3 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

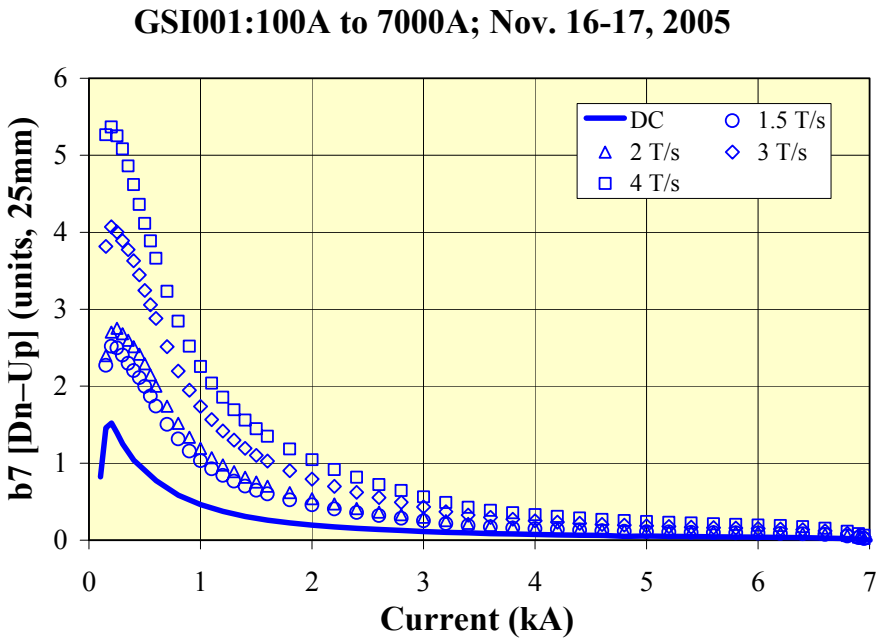

GSI001:100A to 7000A; Nov. 16-17, 2005
b4 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

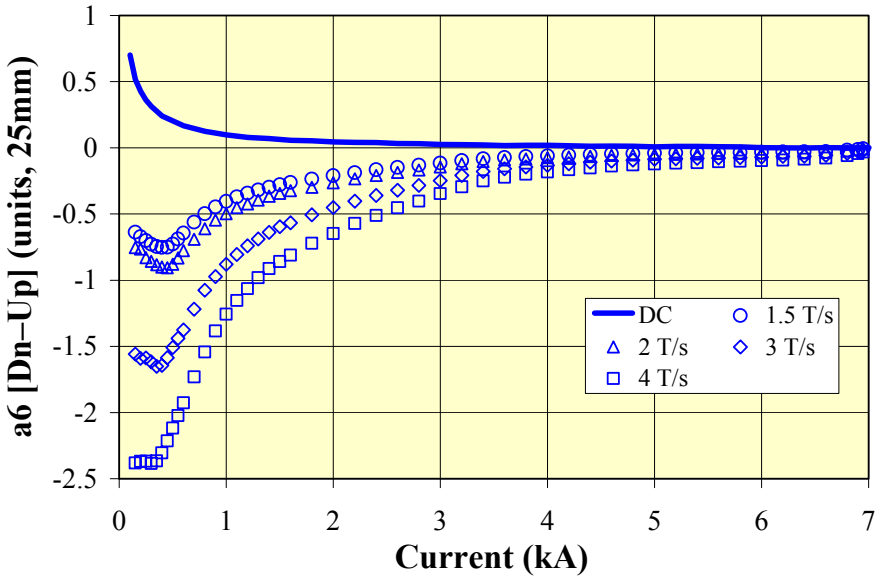

GSI001:100A to 7000A; Nov. 16-17, 2005
b5 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

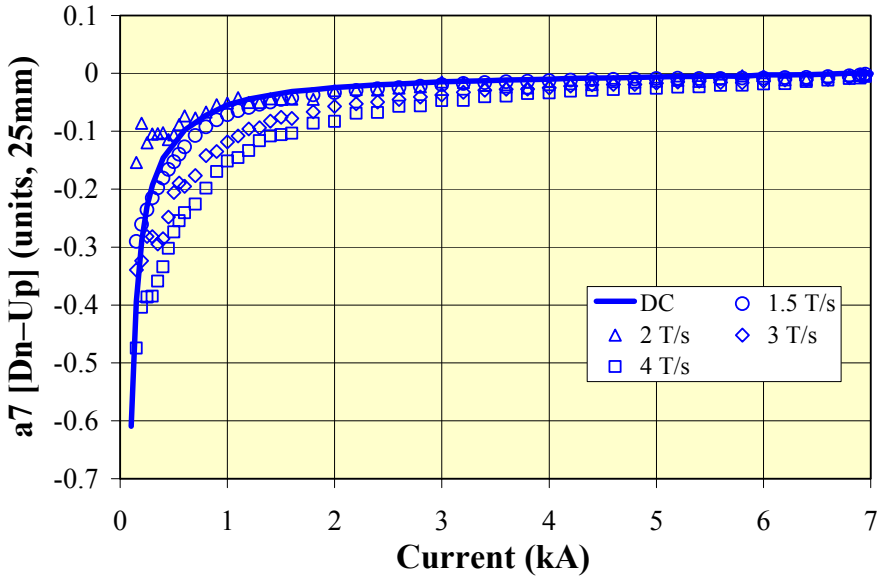

a4 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

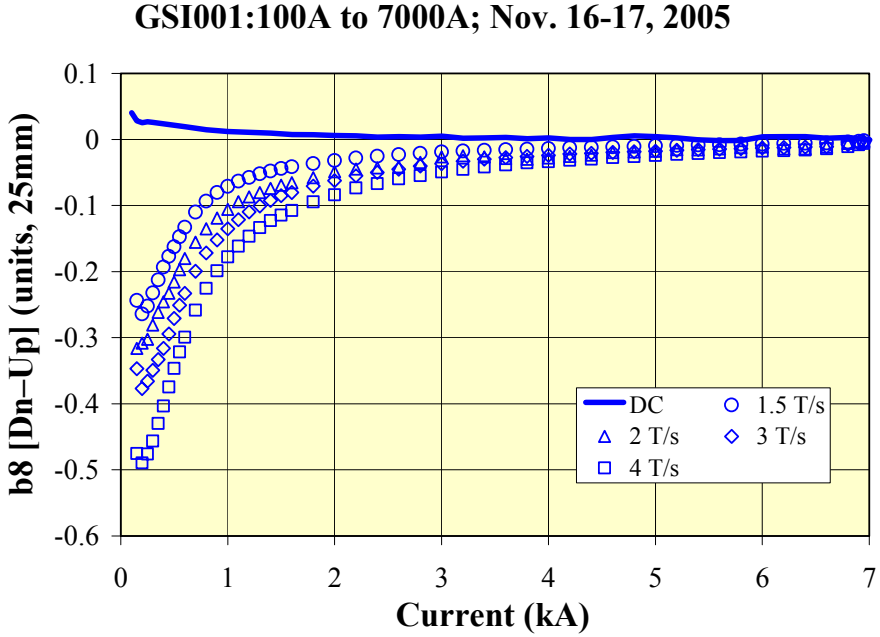

a5 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

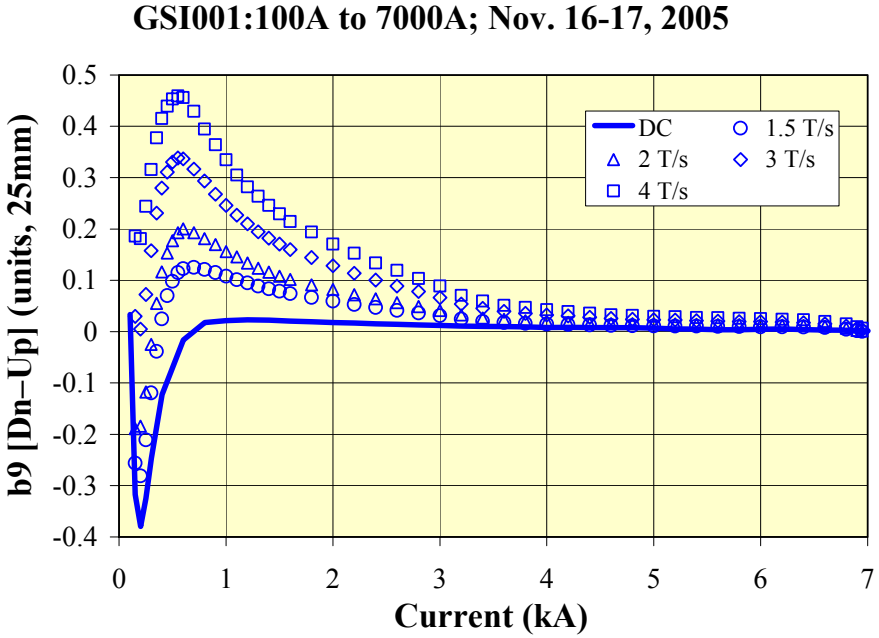

GSI001:100A to 7000A; Nov. 16-17, 2005
b6 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

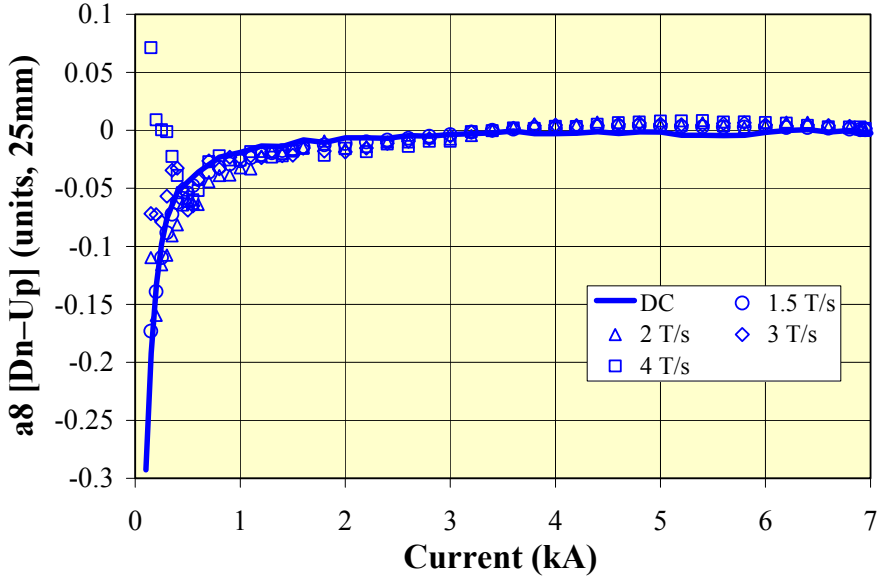

GSI001:100A to 7000A; Nov. 16-17, 2005
b7 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

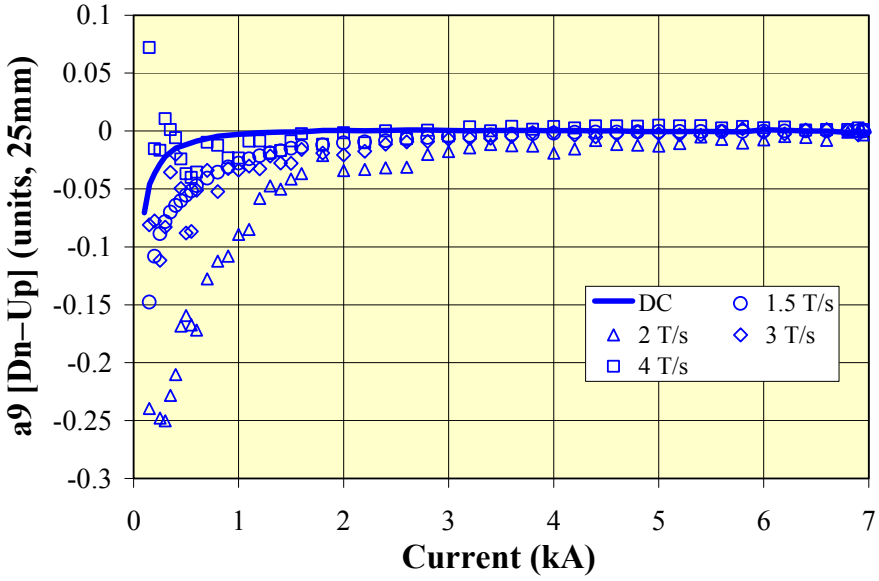

a6 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

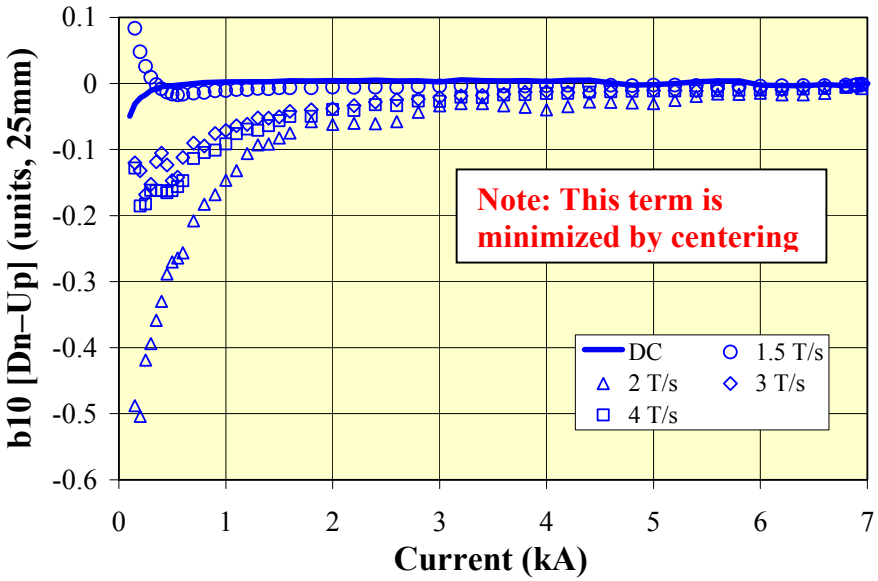

a7 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

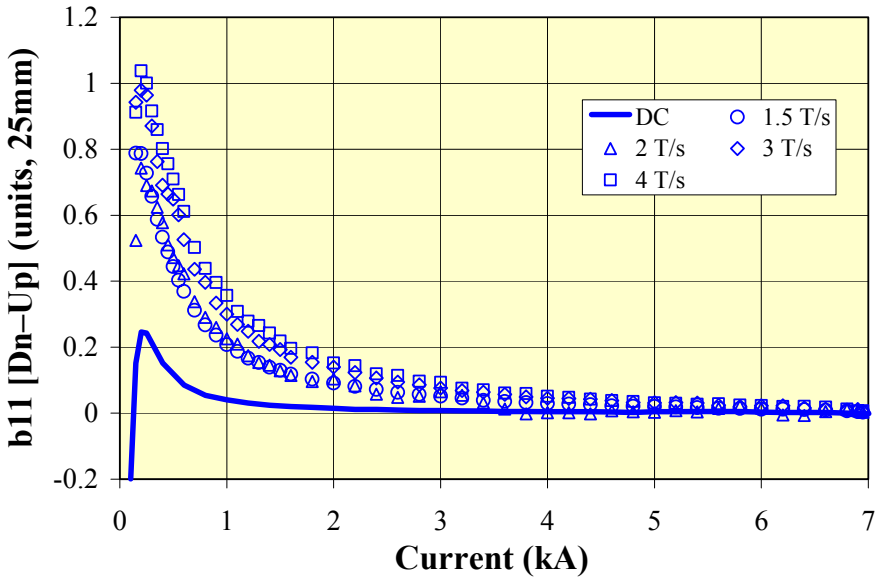

GSI001:100A to 7000A; Nov. 16-17, 2005
b8 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s


GSI001:100A to 7000A; Nov. 16-17, 2005
b9 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s


a8 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s


a9 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s


GSI001:100A to 7000A; Nov. 16-17, 2005
b10 [Dn–Up] (units, 25mm)
Current (kA)
Note: This term is minimized by centering
DC
1.5 T/s
2 T/s
3 T/s
4 T/s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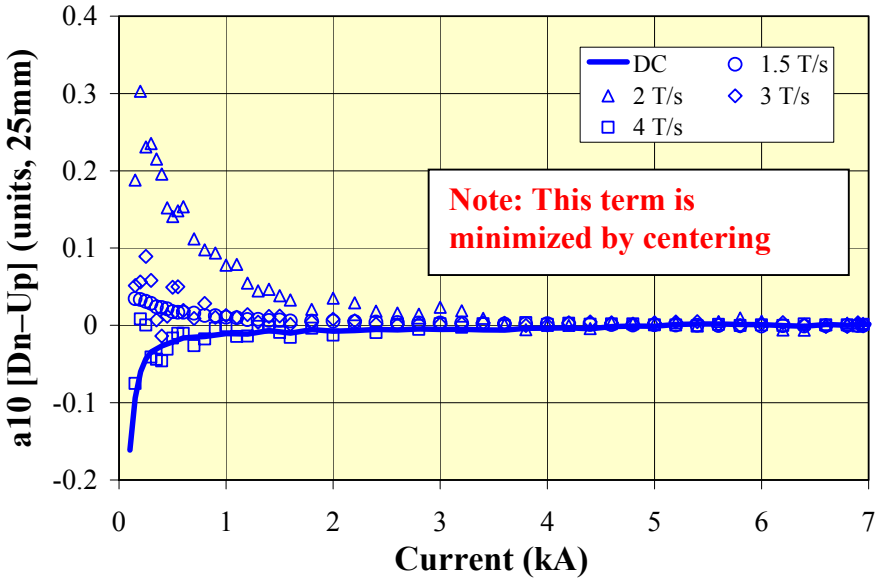
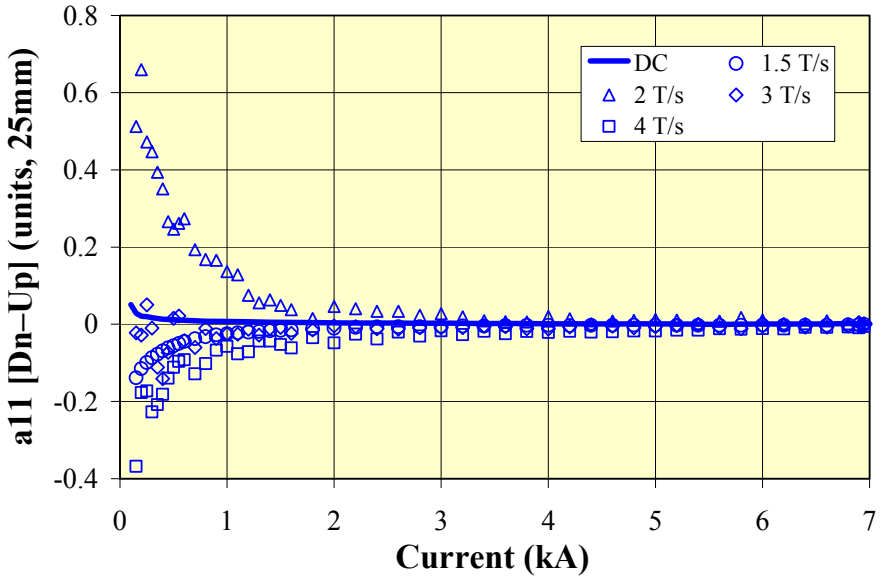
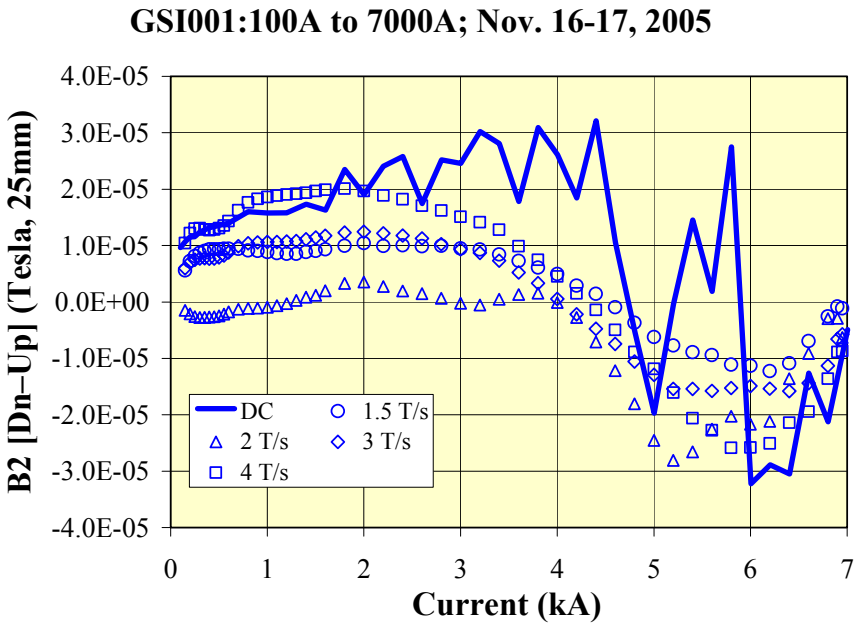
b11 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s


a10 [Dn–Up] (units, 25mm)
Current (kA)
Note: This term is minimized by centering
DC
1.5 T/s
2 T/s
3 T/s
4 T/s


a11 [Dn–Up] (units, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s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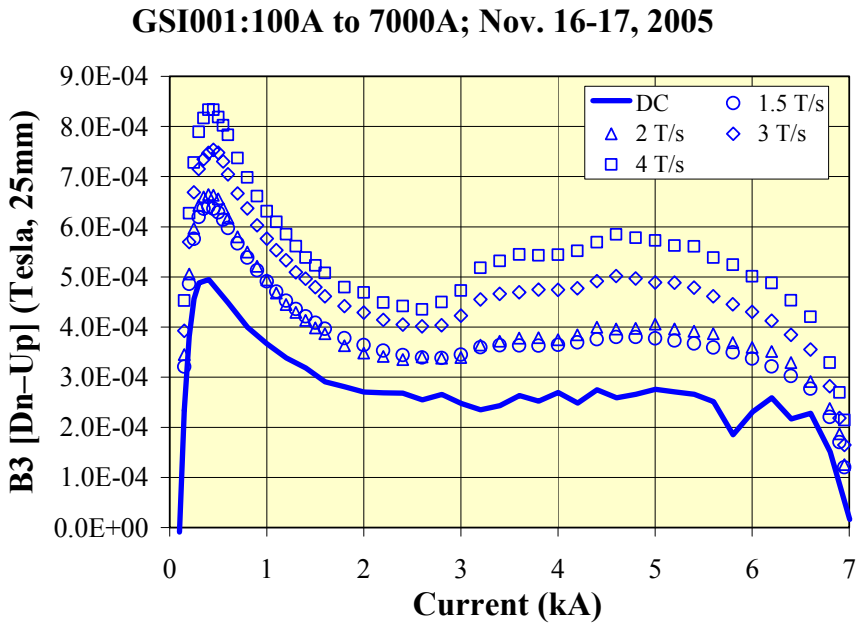
B2 [Dn–Up] (Tesla, 25mm)
4.0E-05
3.0E-05
2.0E-05
1.0E-05
0.0E+00
-1.0E-05
-2.0E-05
-3.0E-05
-4.0E-05
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s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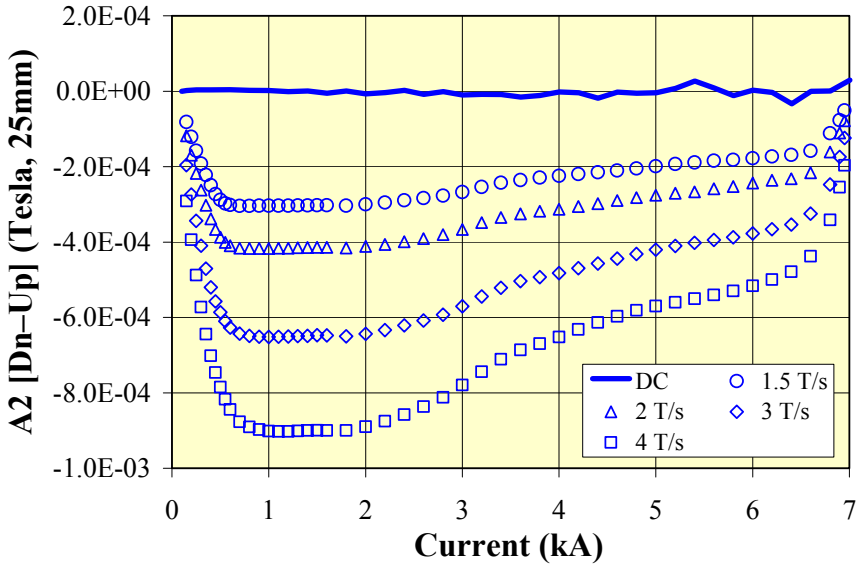
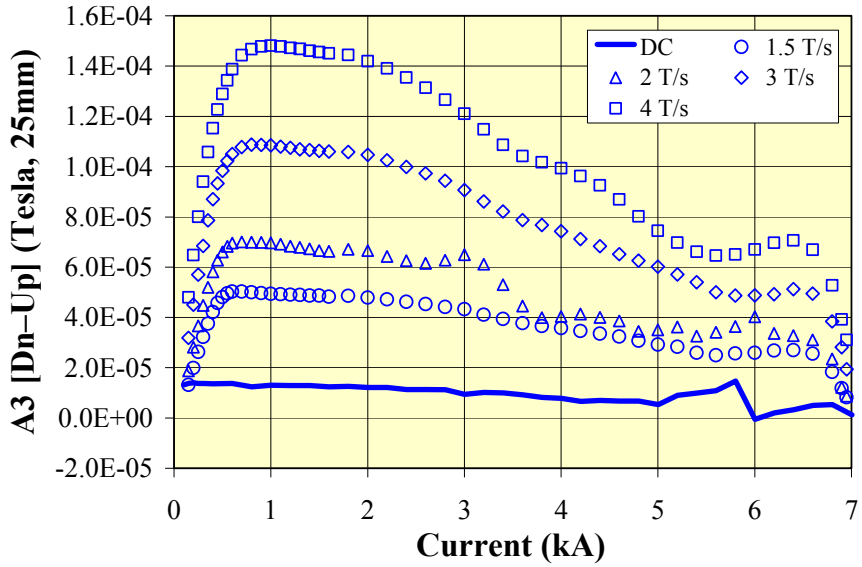
B3 [Dn–Up] (Tesla, 25mm)
9.0E-04
8.0E-04
7.0E-04
6.0E-04
5.0E-04
4.0E-04
3.0E-04
2.0E-04
1.0E-04
0.0E+00
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s


A2 [Dn–Up] (Tesla, 25mm)
2.0E-04
0.0E+00
-2.0E-04
-4.0E-04
-6.0E-04
-8.0E-04
-1.0E-03
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s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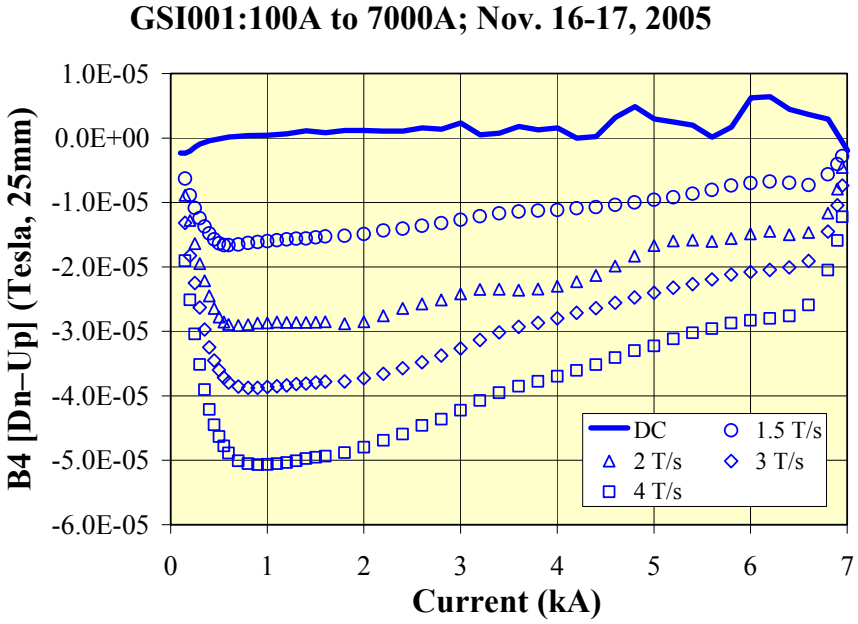
1.6E-04
1.4E-04
1.2E-04
1.0E-04
8.0E-05
6.0E-05
4.0E-05
2.0E-05
0.0E+00
-2.0E-05
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s


GSI001:100A to 7000A; Nov. 16-17, 2005
B4 [Dn–Up] (Tesla, 25mm)
1.0E-05
0.0E+00
-1.0E-05
-2.0E-05
-3.0E-05
-4.0E-05
-5.0E-05
-6.0E-05
0
1
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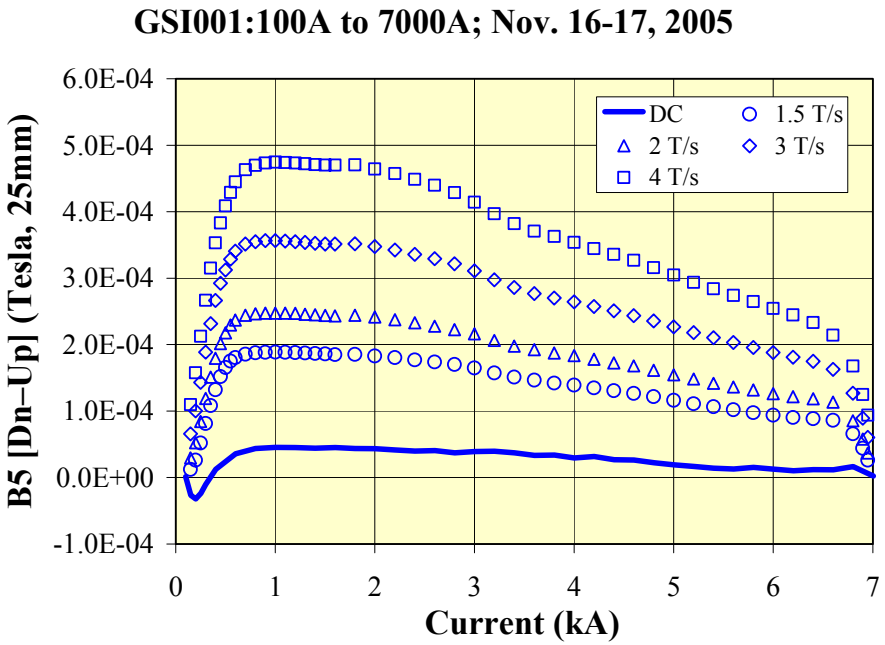
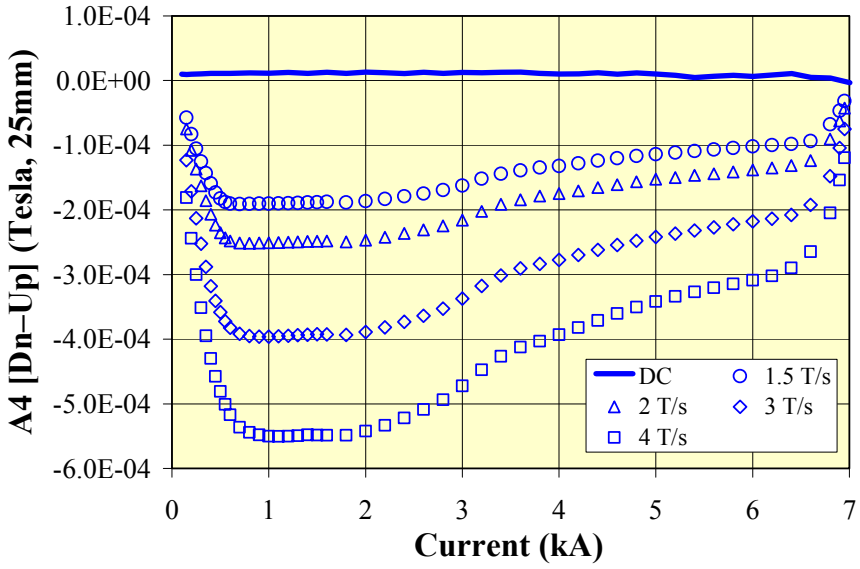
DC
1.5 T/s
2 T/s
3 T/s
4 T/s


GSI001:100A to 7000A; Nov. 16-17, 2005
B5 [Dn–Up] (Tesla, 25mm)
6.0E-04
5.0E-04
4.0E-04
3.0E-04
2.0E-04
1.0E-04
0.0E+00
-1.0E-04
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s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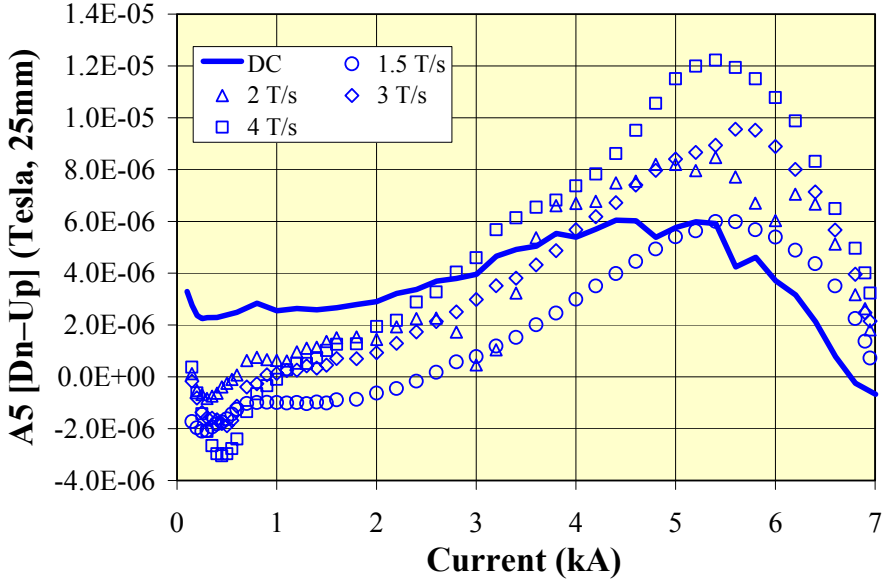
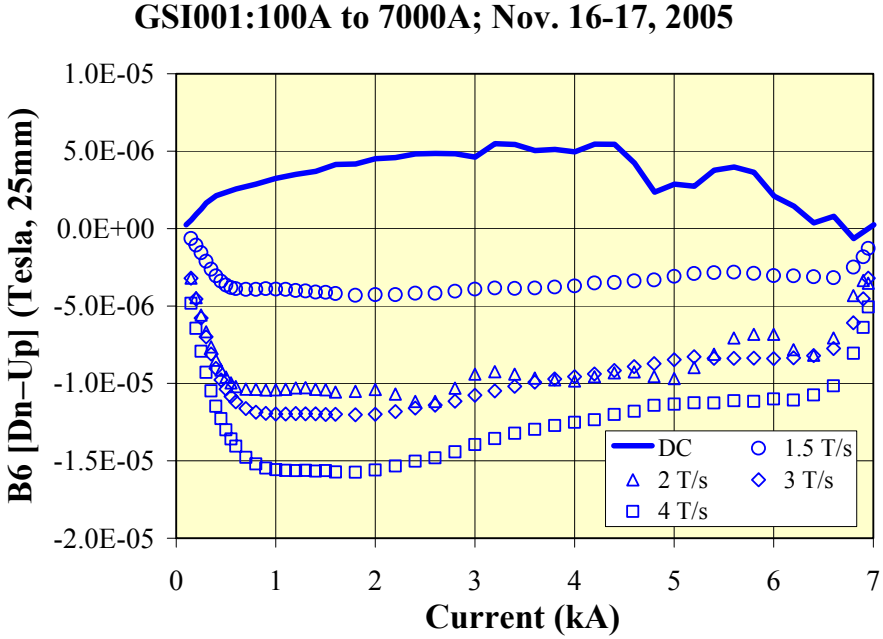
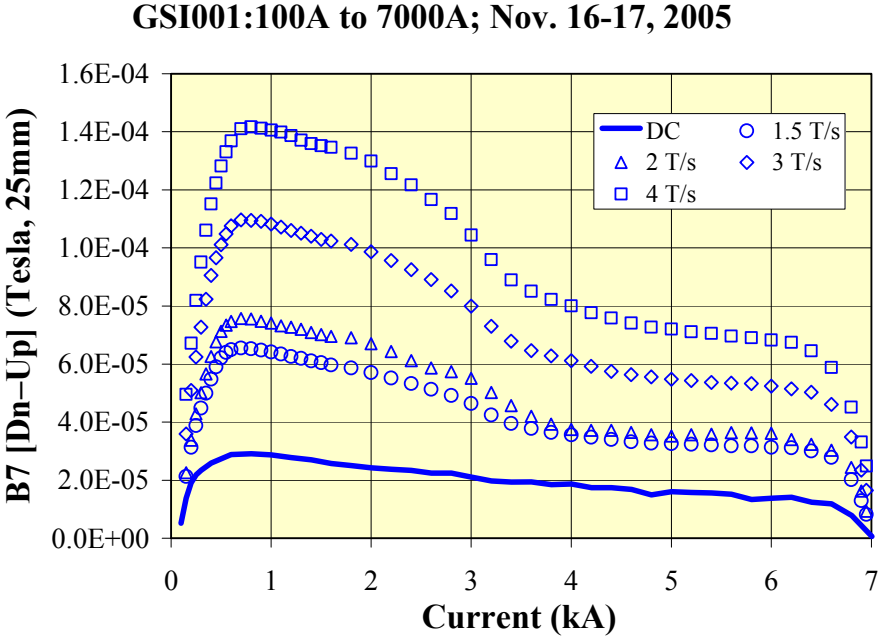
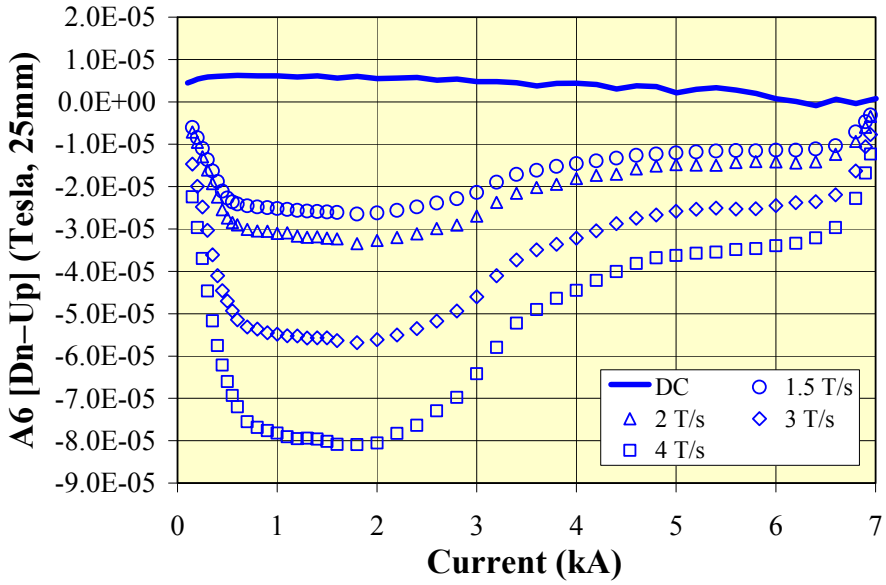
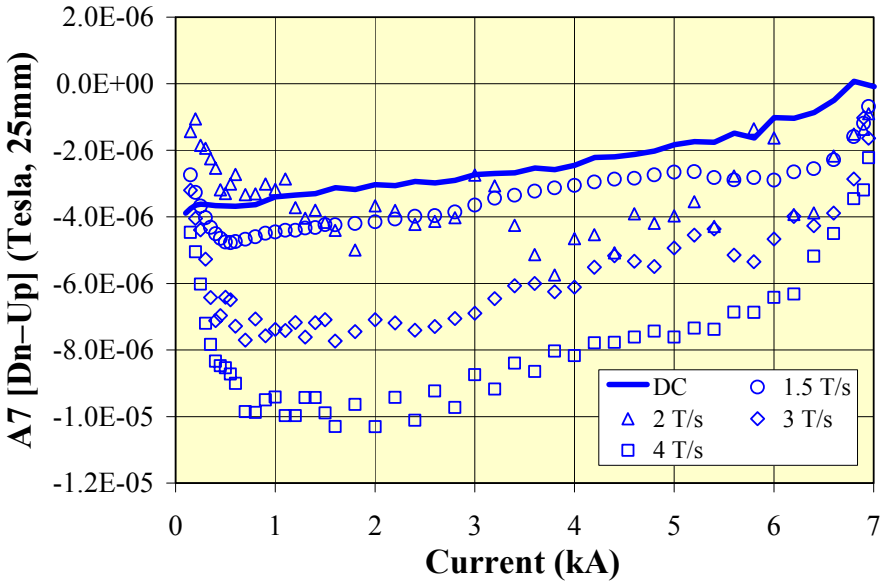
1.0E-04
0.0E+00
-1.0E-04
-2.0E-04
-3.0E-04
-4.0E-04
-5.0E-04
-6.0E-04
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

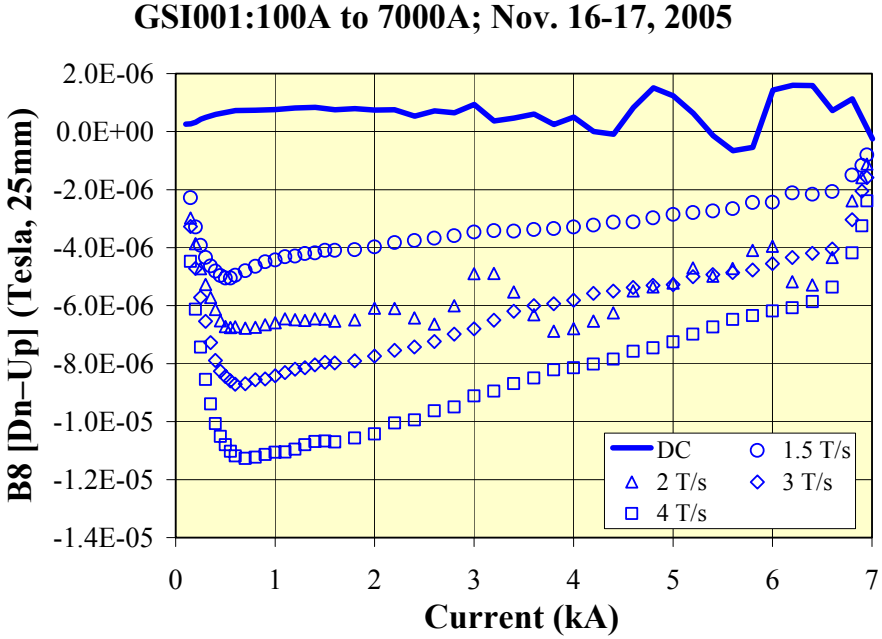

A5 [Dn–Up] (Tesla, 25mm)
1.4E-05
1.2E-05
1.0E-05
8.0E-06
6.0E-06
4.0E-06
2.0E-06
0.0E+00
-2.0E-06
-4.0E-06
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

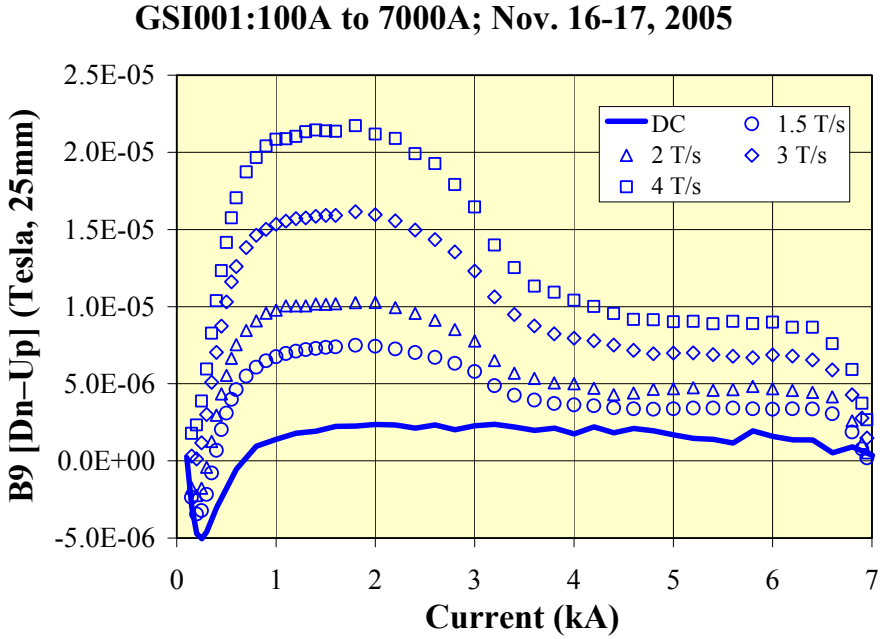

GSI001:100A to 7000A; Nov. 16-17, 2005
B6 [Dn–Up] (Tesla, 25mm)
1.0E-05
5.0E-06
0.0E+00
-5.0E-06
-1.0E-05
-1.5E-05
-2.0E-05
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

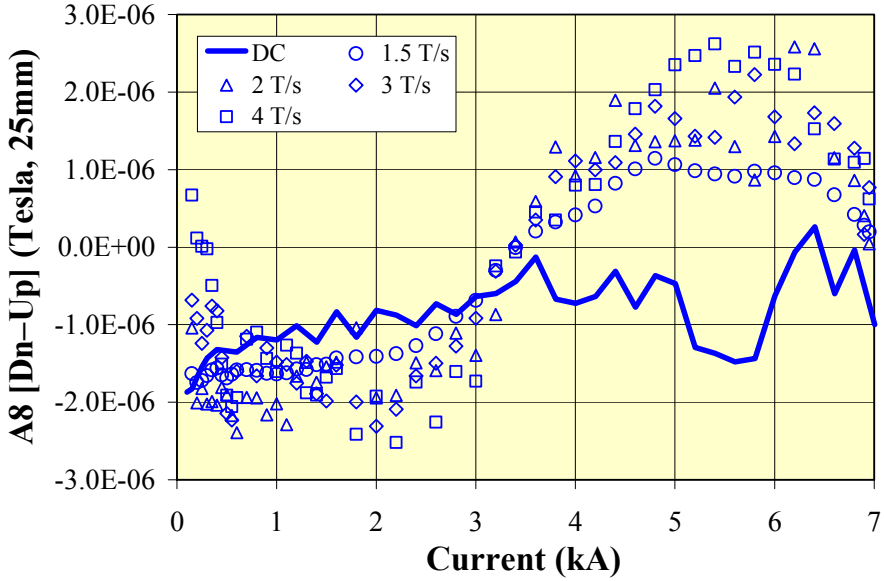

GSI001:100A to 7000A; Nov. 16-17, 2005
B7 [Dn–Up] (Tesla, 25mm)
1.6E-04
1.4E-04
1.2E-04
1.0E-04
8.0E-05
6.0E-05
4.0E-05
2.0E-05
0.0E+00
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

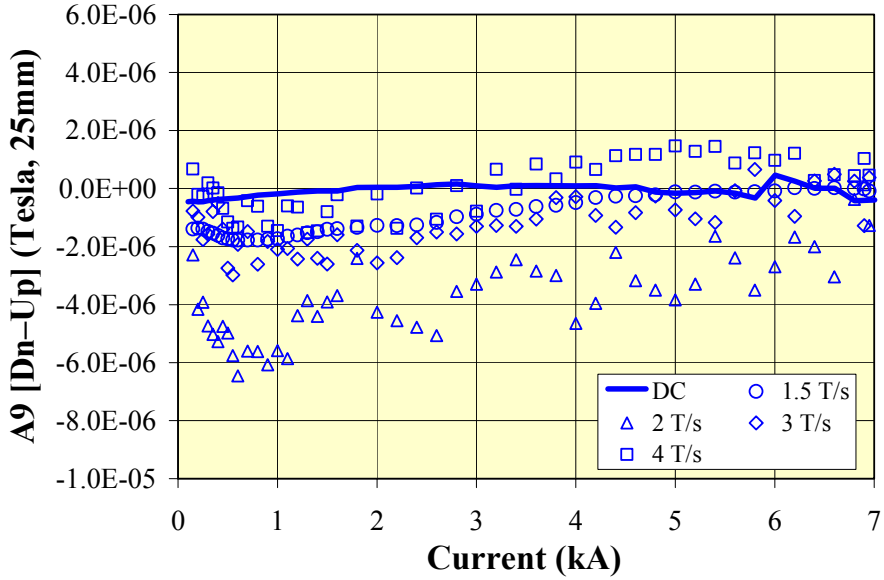

A6 [Dn–Up] (Tesla, 25mm)
2.0E-05
1.0E-05
0.0E+00
-1.0E-05
-2.0E-05
-3.0E-05
-4.0E-05
-5.0E-05
-6.0E-05
-7.0E-05
-8.0E-05
-9.0E-05
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

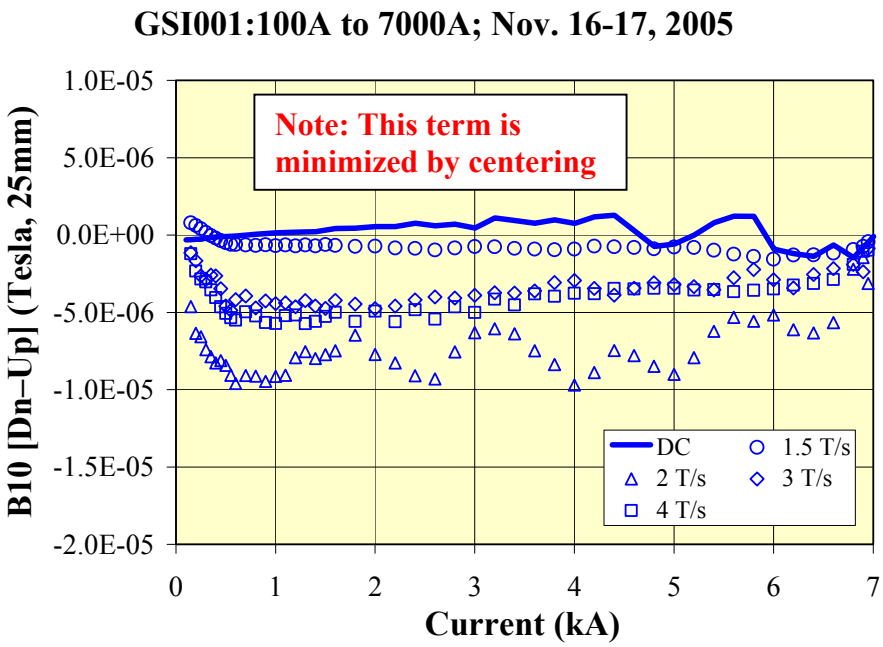

A7 [Dn–Up] (Tesla, 25mm)
2.0E-06
0.0E+00
-2.0E-06
-4.0E-06
-6.0E-06
-8.0E-06
-1.0E-05
-1.2E-05
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

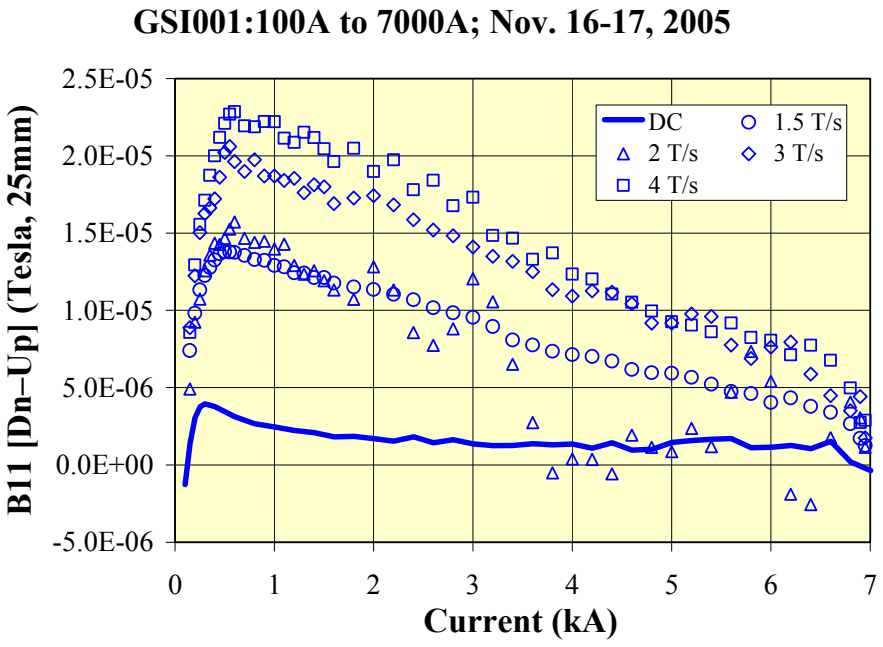

GSI001:100A to 7000A; Nov. 16-17, 2005
B8 [Dn–Up] (Tesla, 25mm)
2.0E-06
0.0E+00
-2.0E-06
-4.0E-06
-6.0E-06
-8.0E-06
-1.0E-05
-1.2E-05
-1.4E-05
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

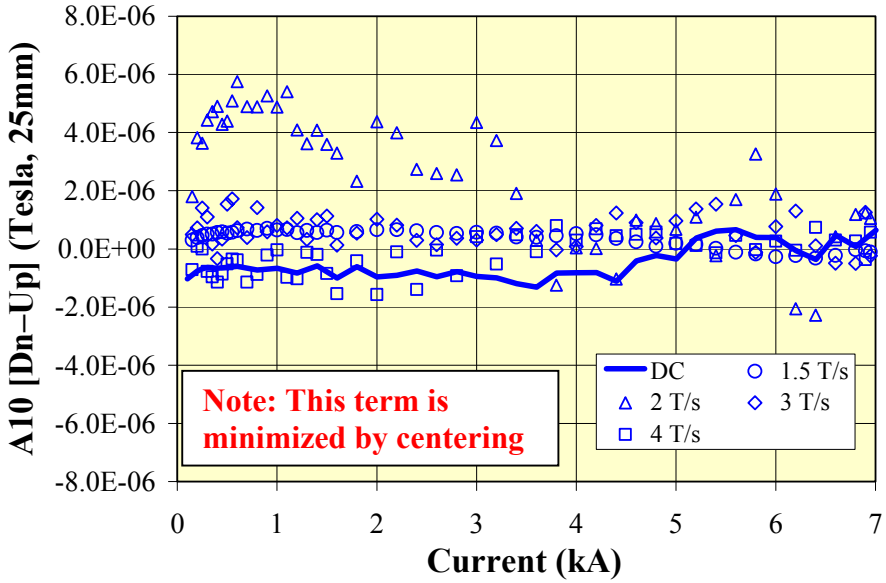

GSI001:100A to 7000A; Nov. 16-17, 2005
B9 [Dn–Up] (Tesla, 25mm)
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
-5.0E-06
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

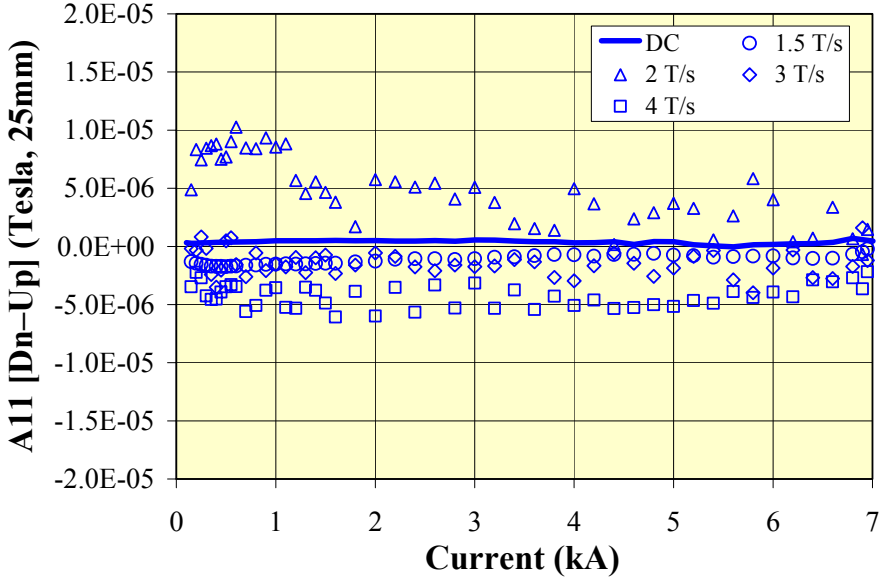

A8 [Dn–Up] (Tesla, 25mm)
3.0E-06
2.0E-06
1.0E-06
0.0E+00
-1.0E-06
-2.0E-06
-3.0E-06
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

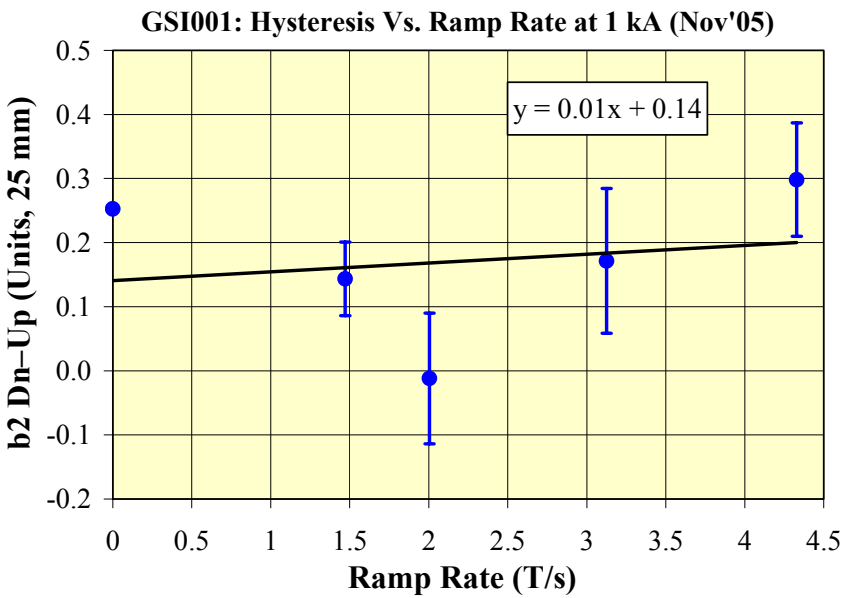

A9 [Dn–Up] (Tesla, 25mm)
6.0E-06
4.0E-06
2.0E-06
0.0E+00
-2.0E-06
-4.0E-06
-6.0E-06
-8.0E-06
-1.0E-05
0
1
2
3
4
5
6
7
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

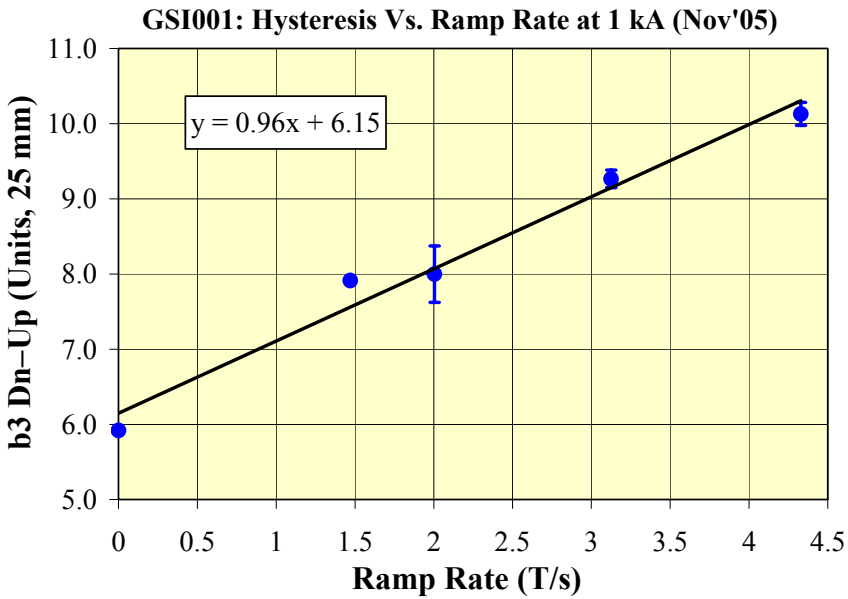

GSI001:100A to 7000A; Nov. 16-17, 2005
B10 [Dn–Up] (Tesla, 25mm)
Current (kA)
Note: This term is minimized by centering
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

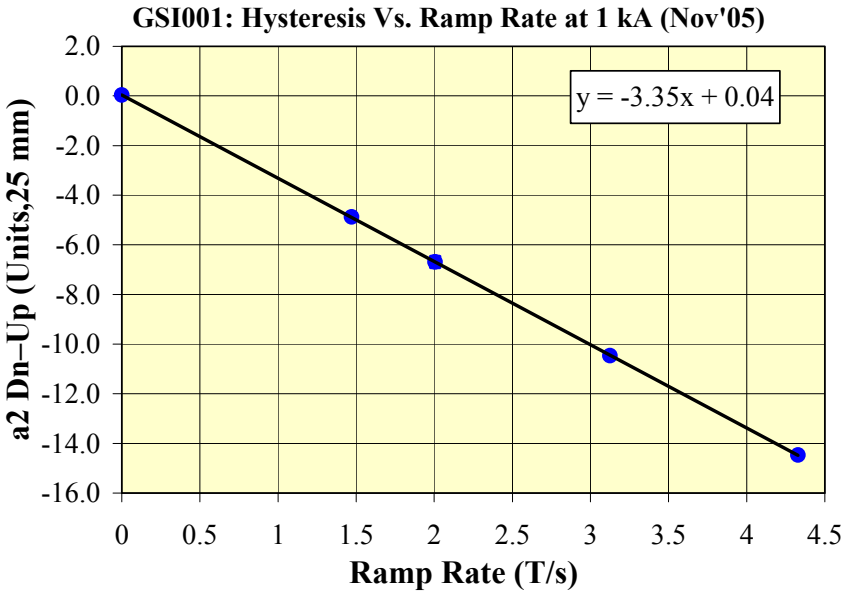

GSI001:100A to 7000A; Nov. 16-17, 2005
B11 [Dn–Up] (Tesla, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

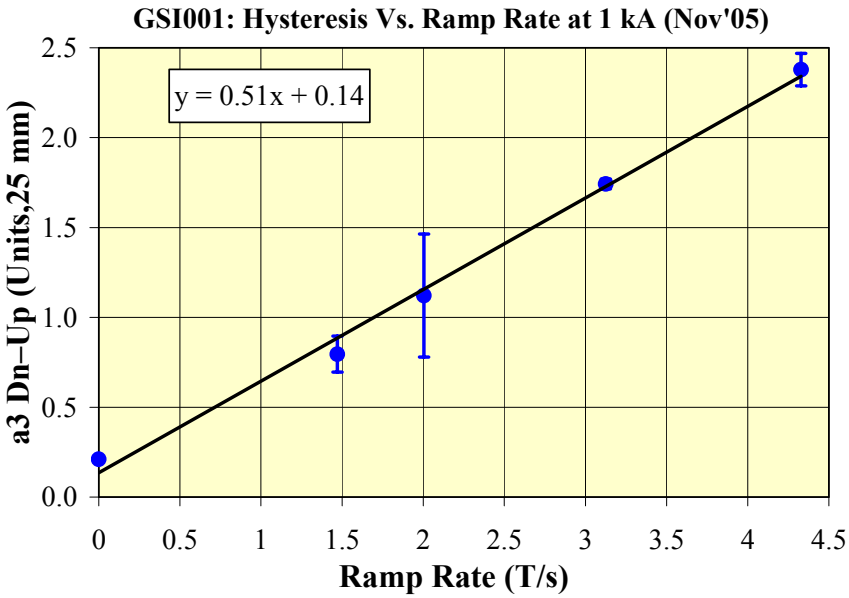

A10 [Dn–Up] (Tesla, 25mm)
Current (kA)
Note: This term is minimized by centering
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

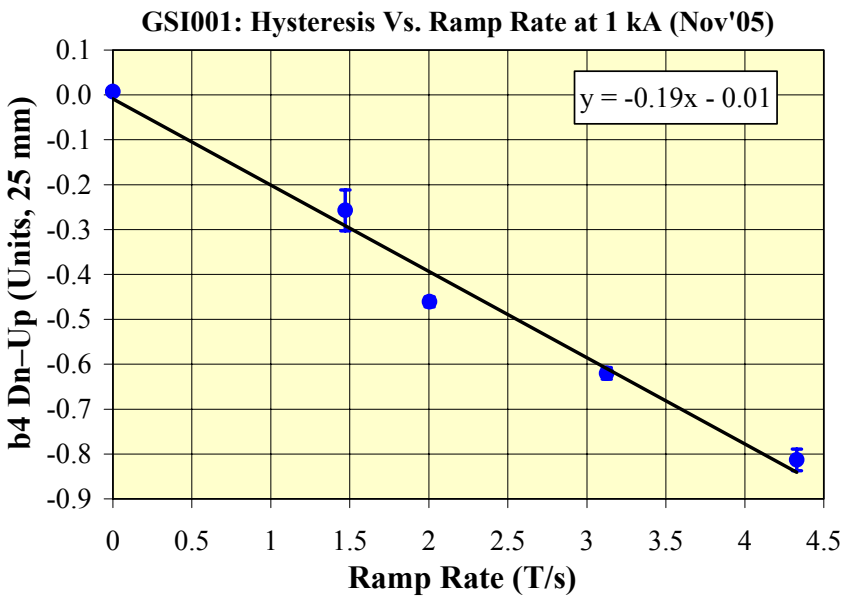

A11 [Dn–Up] (Tesla, 25mm)
Current (kA)
DC
1.5 T/s
2 T/s
3 T/s
4 T/s

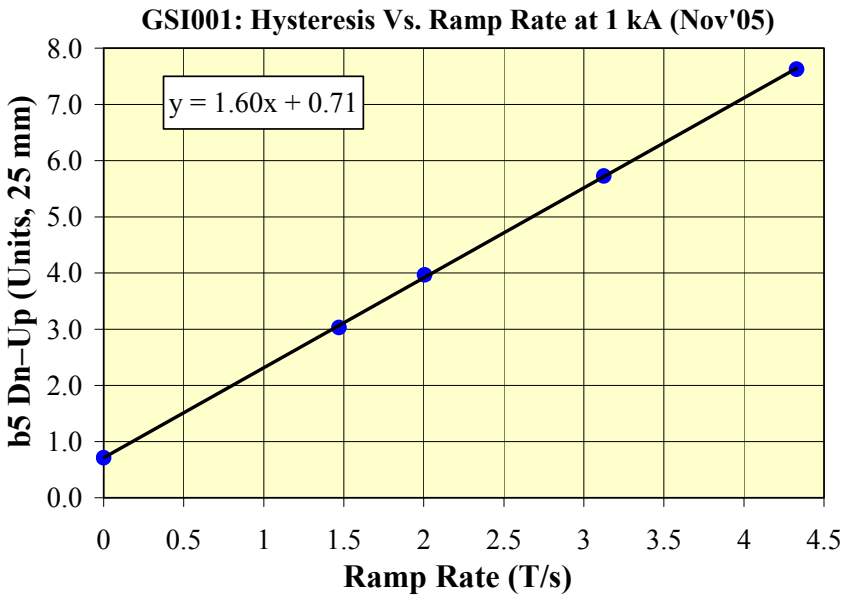

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
y = 0.01x + 0.14
b2 Dn–Up (Units, 25 mm)
Ramp Rate (T/s)

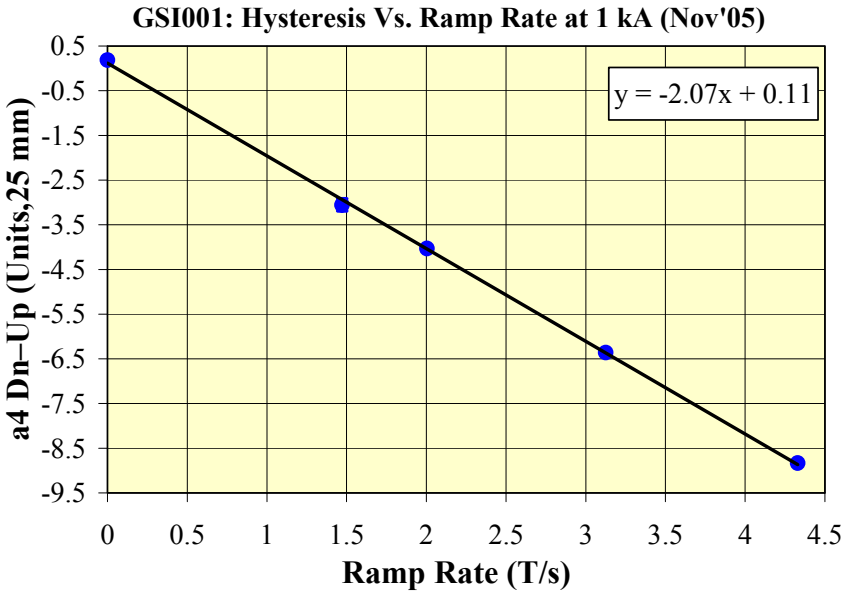

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
y = 0.96x + 6.15
b3 Dn–Up (Units, 25 mm)
Ramp Rate (T/s)

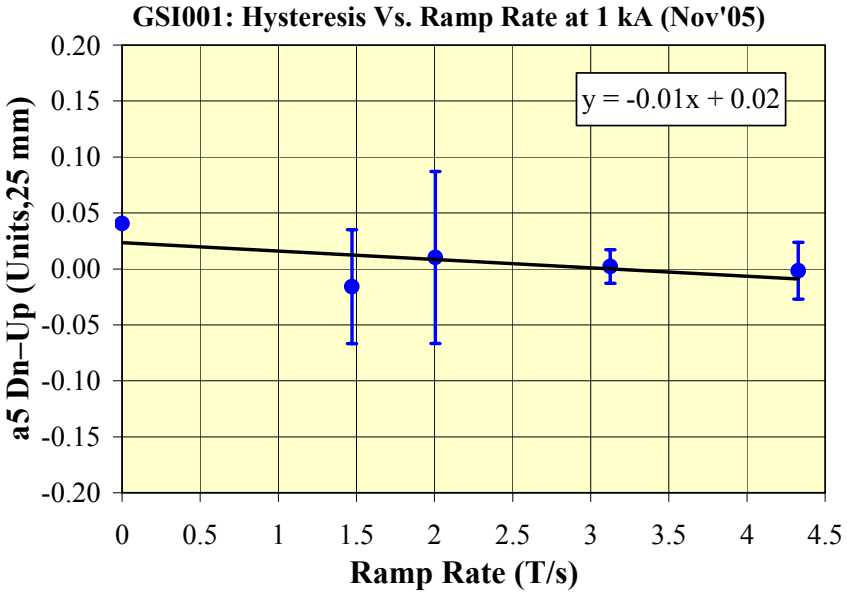

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
y = -3.35x + 0.04
a2 Dn–Up (Units,25 mm)
Ramp Rate (T/s)

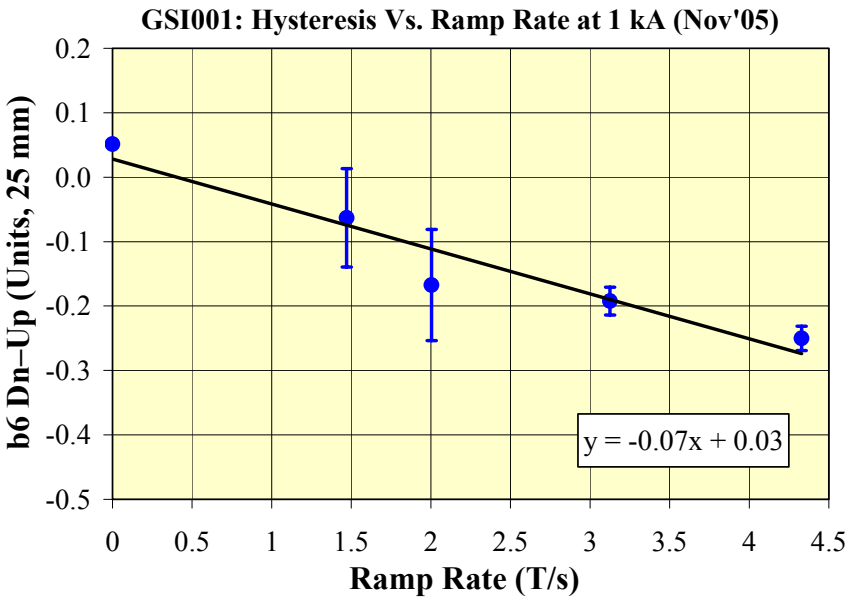

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
y = 0.51x + 0.14
a3 Dn–Up (Units,25 mm)
Ramp Rate (T/s)

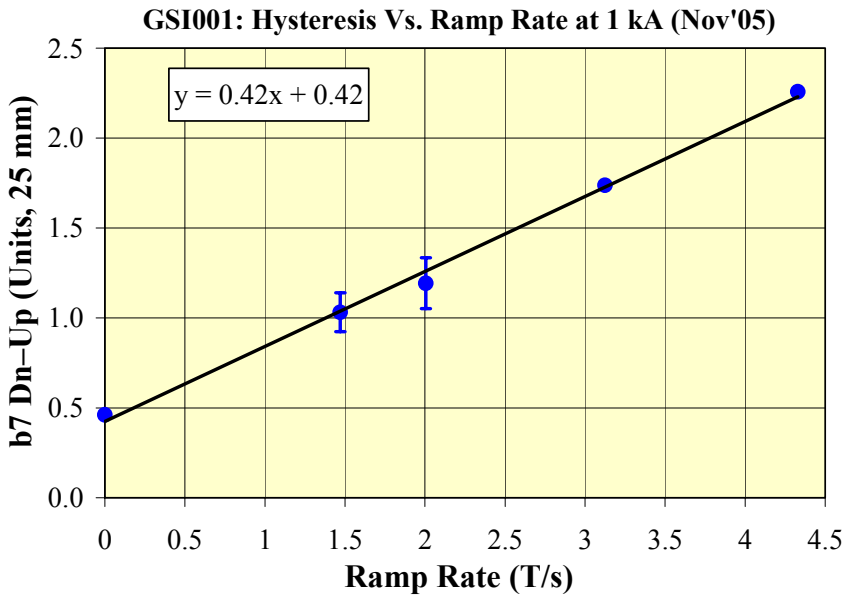

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
y = -0.19x - 0.01
b4 Dn–Up (Units, 25 mm)
Ramp Rate (T/s)

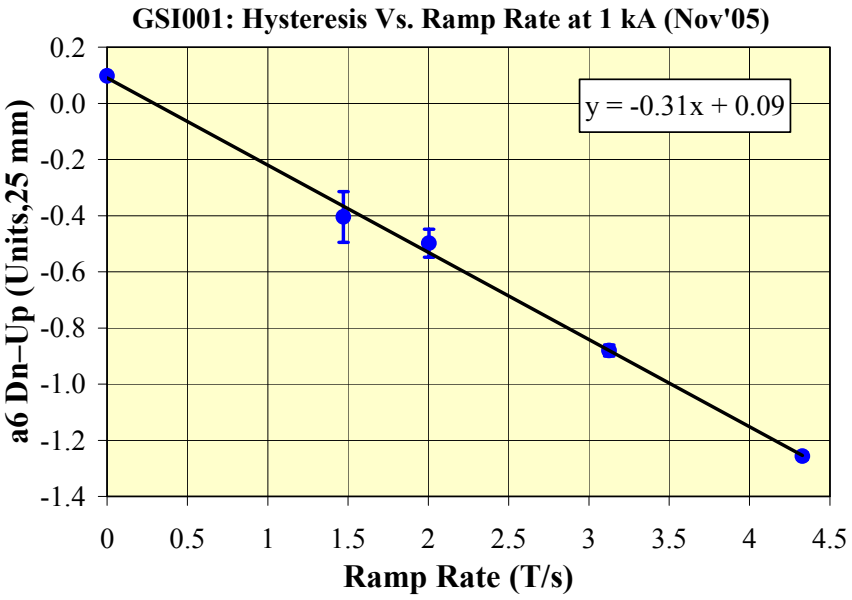

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
y = 1.60x + 0.71
b5 Dn–Up (Units, 25 mm)
Ramp Rate (T/s)

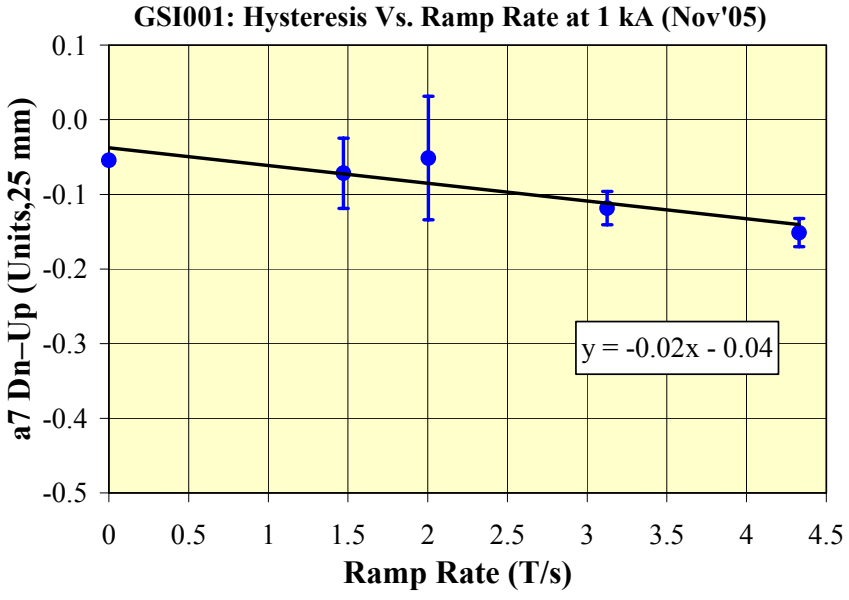

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
y = -2.07x + 0.11
a4 Dn–Up (Units,25 mm)
Ramp Rate (T/s)

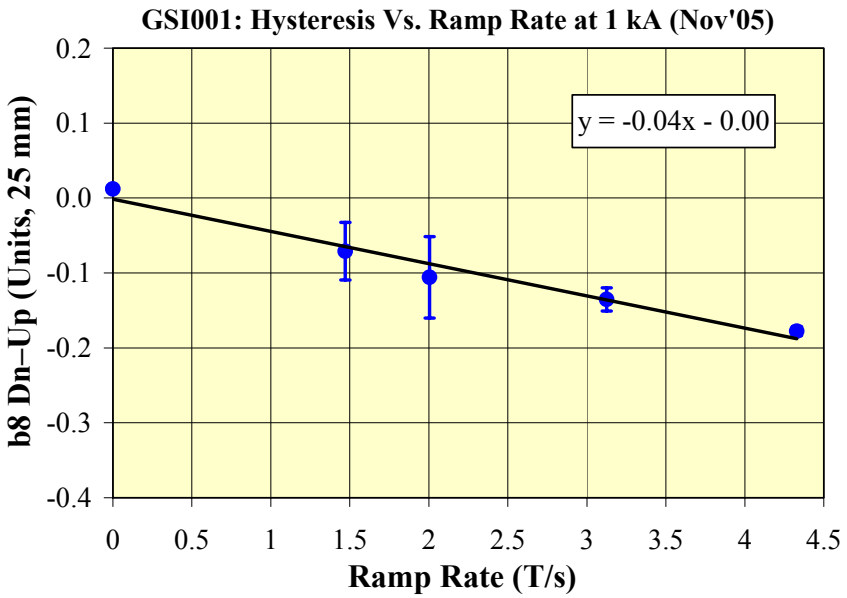

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
y = -0.01x + 0.02
a5 Dn–Up (Units,25 mm)
Ramp Rate (T/s)

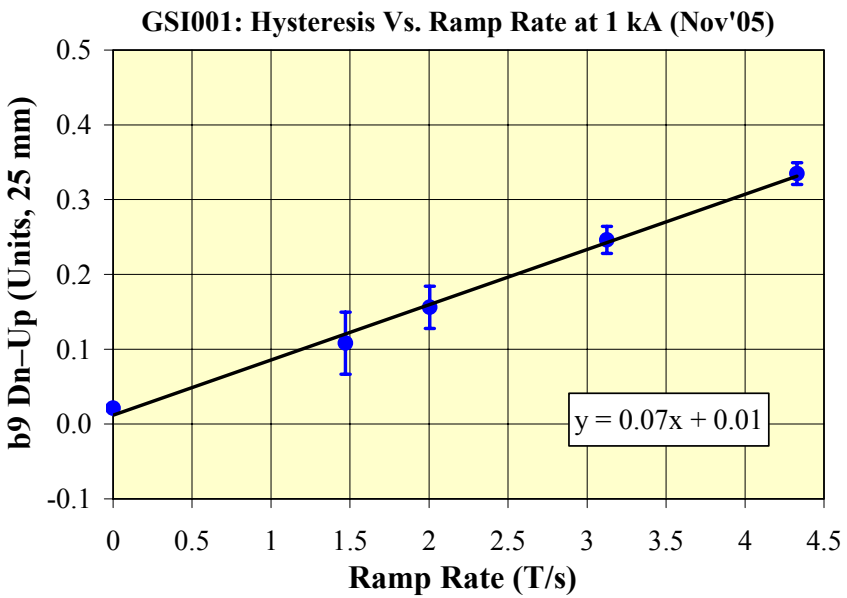

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
b6 Dn–Up (Units, 25 mm)
Ramp Rate (T/s)
y = -0.07x + 0.03

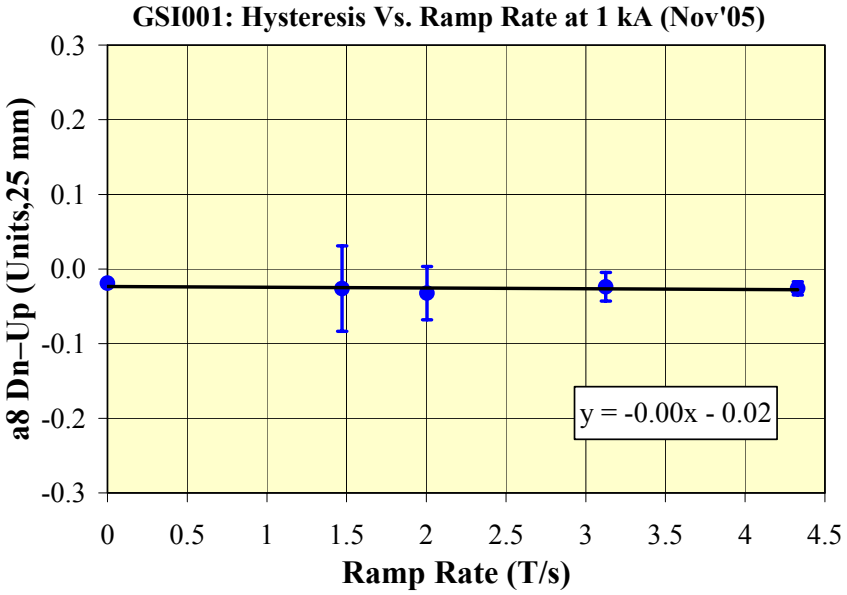

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
b7 Dn–Up (Units, 25 mm)
Ramp Rate (T/s)
y = 0.42x + 0.42

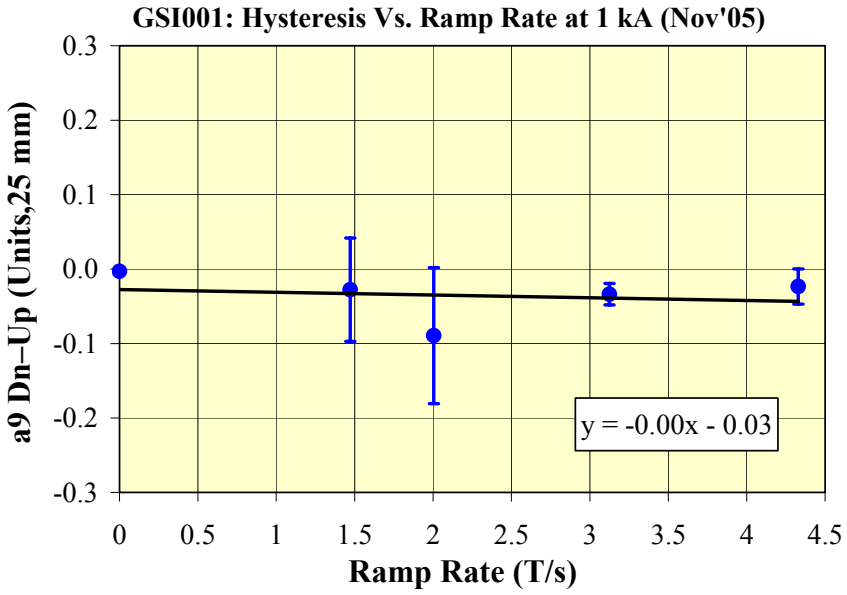

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
a6 Dn–Up (Units,25 mm)
Ramp Rate (T/s)
y = -0.31x + 0.09

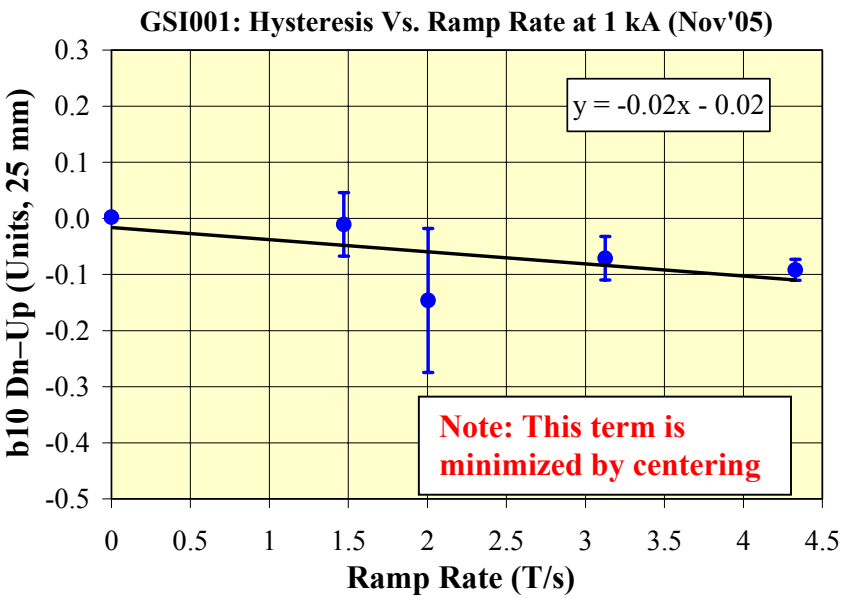

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
a7 Dn–Up (Units,25 mm)
Ramp Rate (T/s)
y = -0.02x - 0.04

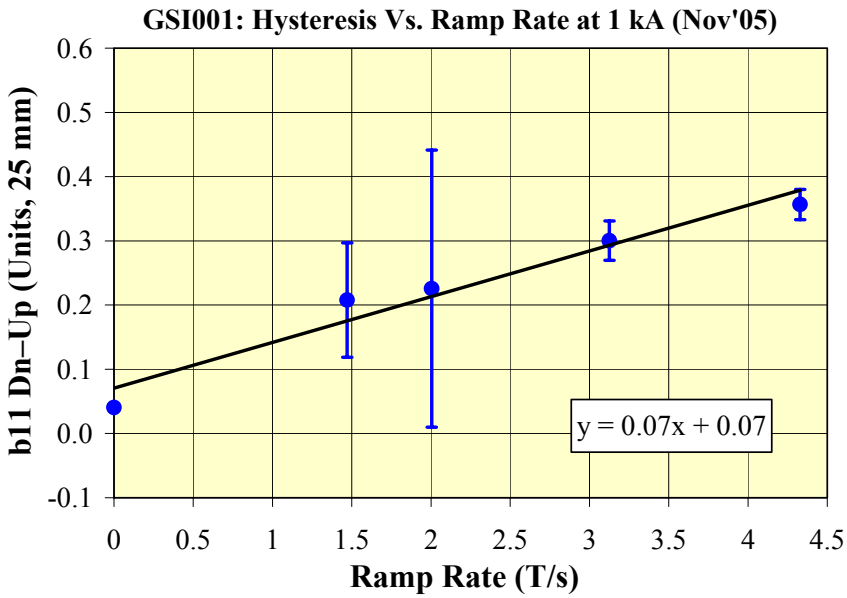

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
b8 Dn–Up (Units, 25 mm)
Ramp Rate (T/s)
y = -0.04x - 0.00

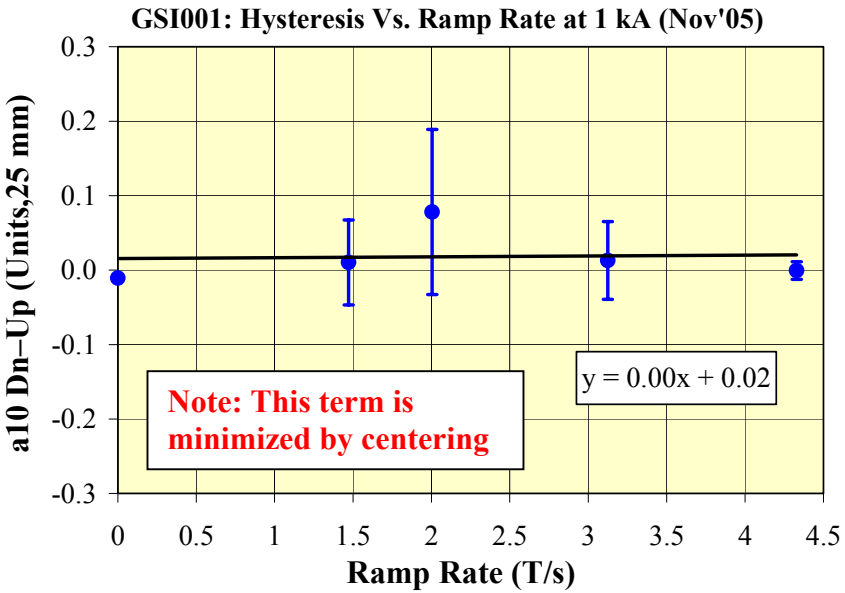

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
b9 Dn–Up (Units, 25 mm)
Ramp Rate (T/s)
y = 0.07x + 0.01

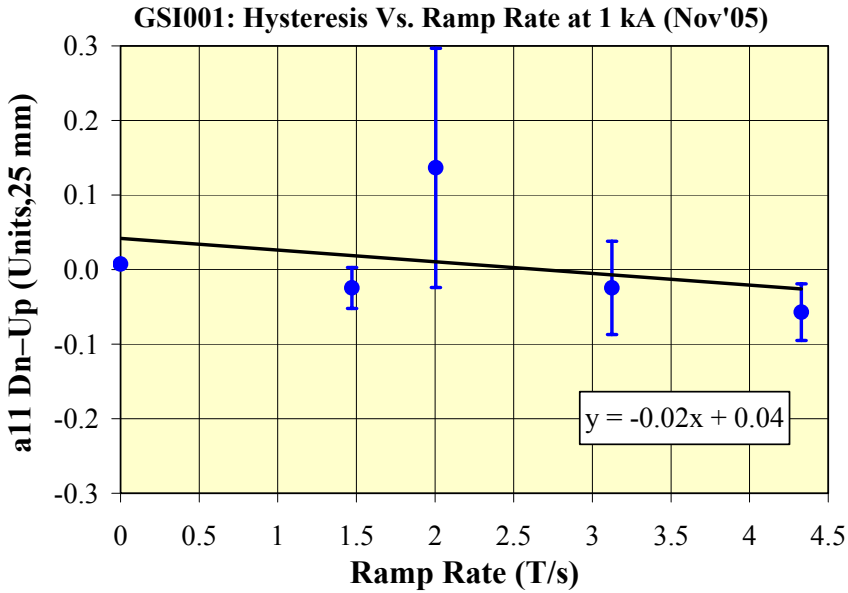

GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
a8 Dn–Up (Units,25 mm)
Ramp Rate (T/s)
y = -0.00x - 0.02


GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
a9 Dn–Up (Units,25 mm)
Ramp Rate (T/s)
y = -0.00x - 0.03


GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
b10 Dn–Up (Units, 25 mm)
Ramp Rate (T/s)
y = -0.02x - 0.02
Note: This term is minimized by centering


GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
b11 Dn–Up (Units, 25 mm)
Ramp Rate (T/s)
y = 0.07x + 0.07


GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
a10 Dn–Up (Units,25 mm)
Ramp Rate (T/s)
y = 0.00x + 0.02
Note: This term is minimized by centering


GSI001: Hysteresis Vs. Ramp Rate at 1 kA (Nov'05)
a11 Dn–Up (Units,25 mm)
Ramp Rate (T/s)
y = -0.02x + 0.04