The Buckley Quads: Hysteresis, Calibration

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The Weak Series

There are 41 weak quads, but the manufacturer measured serial numbers 3 through 41 with a rotating probe to find integrated strength S versus excitation current I. Starting from 0 A, up to full intended current of 6 A, back down to zero, switched polarity, to -6 A, back down to zero. This was done in steps of 1 A.

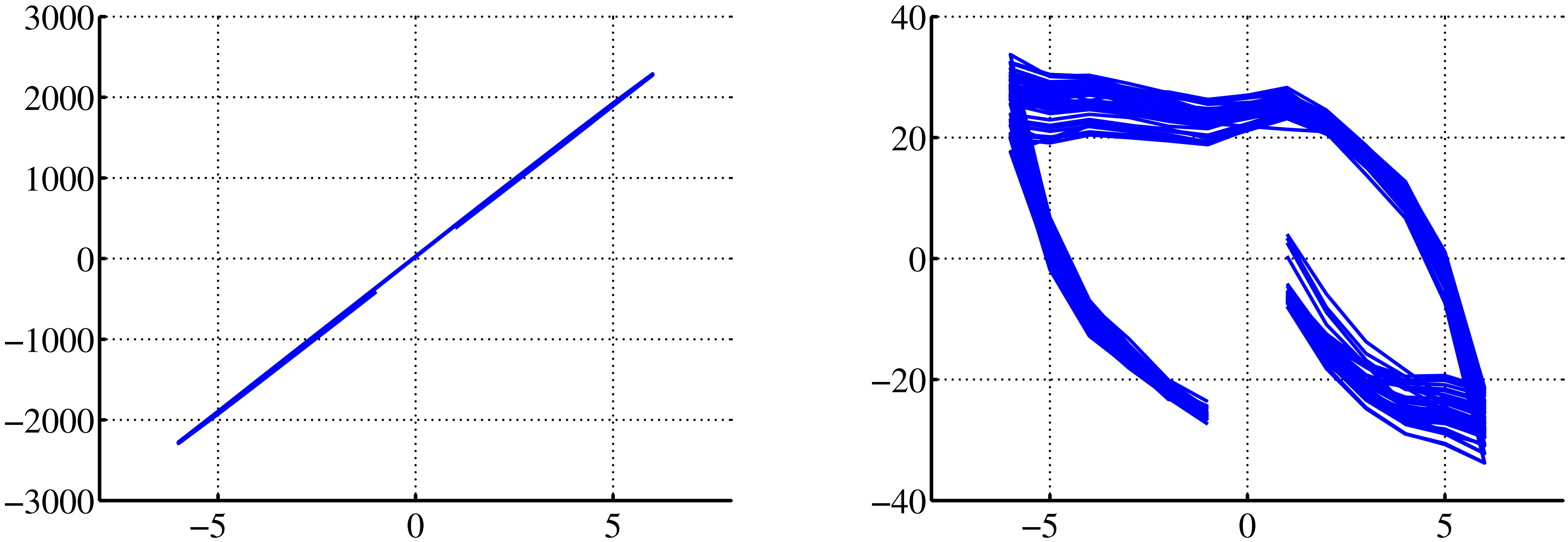

Figure 1: (Left) Measured $S(I) = \int B'(I, s)ds$ curves for Weak quads 3 through 41, and (right) same curves with linear part of 385 Gauss per Amp subtracted. The direction of measurement is counterclockwise, starting at 1 A, ending at -1 A.

Calibration curve without regard to hysteresis

Due to the hysteresis, there is an approximately 50 Gauss difference in integrated strength between increasing and decreasing fields. Thus if no attention is paid towards this effect, the field will be uncertain to ± 25 Gauss.

The integrated gradient fits well to the following function:

$$S = \int B' ds = 2310 \text{ Gauss} \left(\frac{I}{6\,\text{A}}\right) - 25 \text{ Gauss} \left(\frac{I}{6\,\text{A}}\right)^3 \pm 25 \text{ Gauss} \tag{1}$$

Let us define normalized current $\tilde{I} = I/(6\mathrm{A})$, thus,

$$\frac{S}{\text{Gauss}} = 2310\,\tilde{I} - 25\,\tilde{I}^3 \pm 25 \tag{2}$$

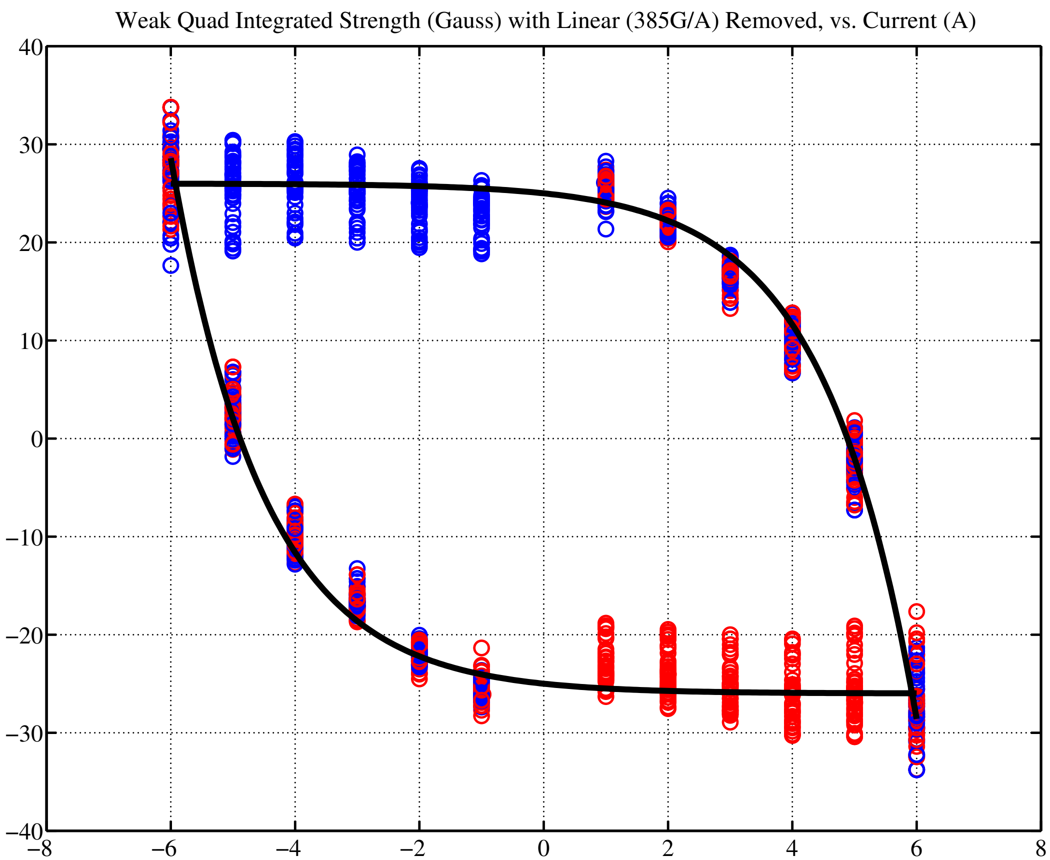

Figure 2: Data of previous Fig., with linear part removed, and omitting the initial points up to 6 A from a demagnetized state. These points are blue. Also in order to give the complete hysteresis loops, plotted are the reversed curves $(-S(-I))$ in red. The exponential fit eqn. 3 is plotted as well, in black.

Calibration curve and overcoming hysteretic effect

Between quads, there is a variation of only $\Delta S = \pm 5$ Gauss.

Also, one notices that although the measurement was started with the quads in a nearly demagnetized state, the deviant at 6 Amperes is stable at -25 Gauss. After coming down, reversing current to -6 Amperes. The deviant is again of same magnitude but opposite sign. This suggests that when powered with a unipolar supply, and provided that the quad has not been magnetized beyond a 6 Ampere excitation, to get a strength given S, one need only raise the excitation to the full 6 Amperes and come down to the appropriate current. The width along this “de-excitation” curve is only $S = \pm 5$ Gauss, so one infers that unipolar power supplies are sufficient as long as the setting need be no more accurate than this value. This “de-excitation” curve has been fitted and is shown as the black curve in the figure.

$$\frac{S}{\text{Gauss}} = 26 + 2310\,\tilde{I} - e^{4\tilde{I}} \pm 5 \tag{3}$$

There is thus a factor 5 improvement in settability using this trick.

If the quad is for some reason magnetized to a larger value than would be obtained with a 6 Amperes power supply, then it must be demagnetized with a bipolar power supply. I suggest that all 41 quads be demagnetized before installation.

The Medium Quads

The only difference between the weak and medium quads is the coils: The weak have 168 turns of enameled wires, whereas the medium have 80 (or so, see below) turns of copper tape on a base that sits against the yoke that is water cooled. Thus, we can directly compare the excitation curves of the two types, since they should give the same integrated field for the same number of Amp-turns.

Again, the $S(I)$ curve can be plotted, but it's more informative to look at the curve with the linear part subtracted. The linear part is 185.0 ± 0.5 Gauss per Amp, whereas the Weak case was 385.0 ± 0.5 Gauss per Amp. These should be in the ratio of the number of turns, $168/80 = 2.1$ but is actually $385/185 = 2.08$. The reason may be that the number of turns on the Medium is 81 rather than 80 (ratio would be 2.074). The turns of wire are easy to quantify, but the turns of tape less so, since it is not possible to have the current enter a pole near the point it exits.

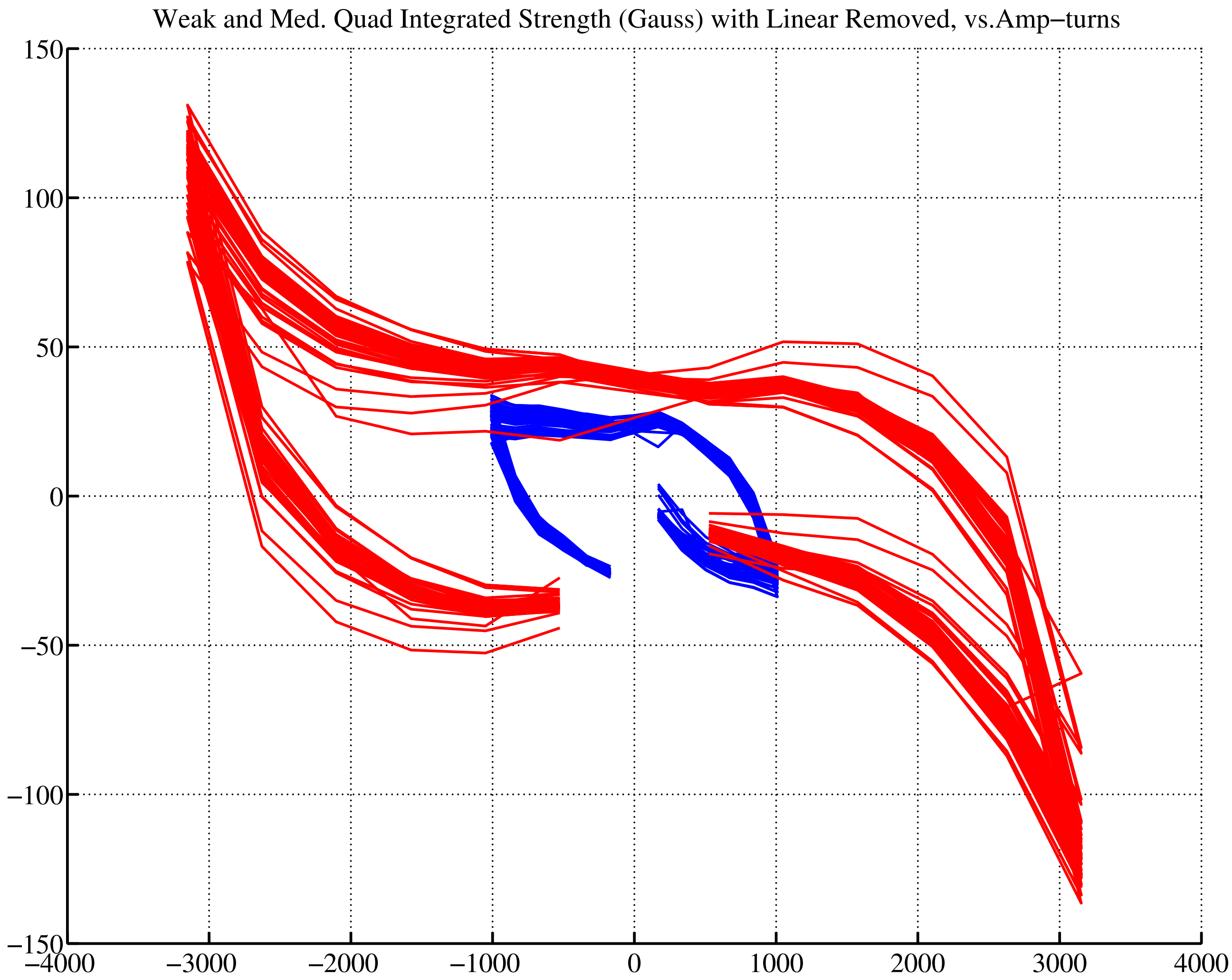

Figure 3: Weak (blue) and the Medium (red) calibration curves with fitted linear parts subtracted.

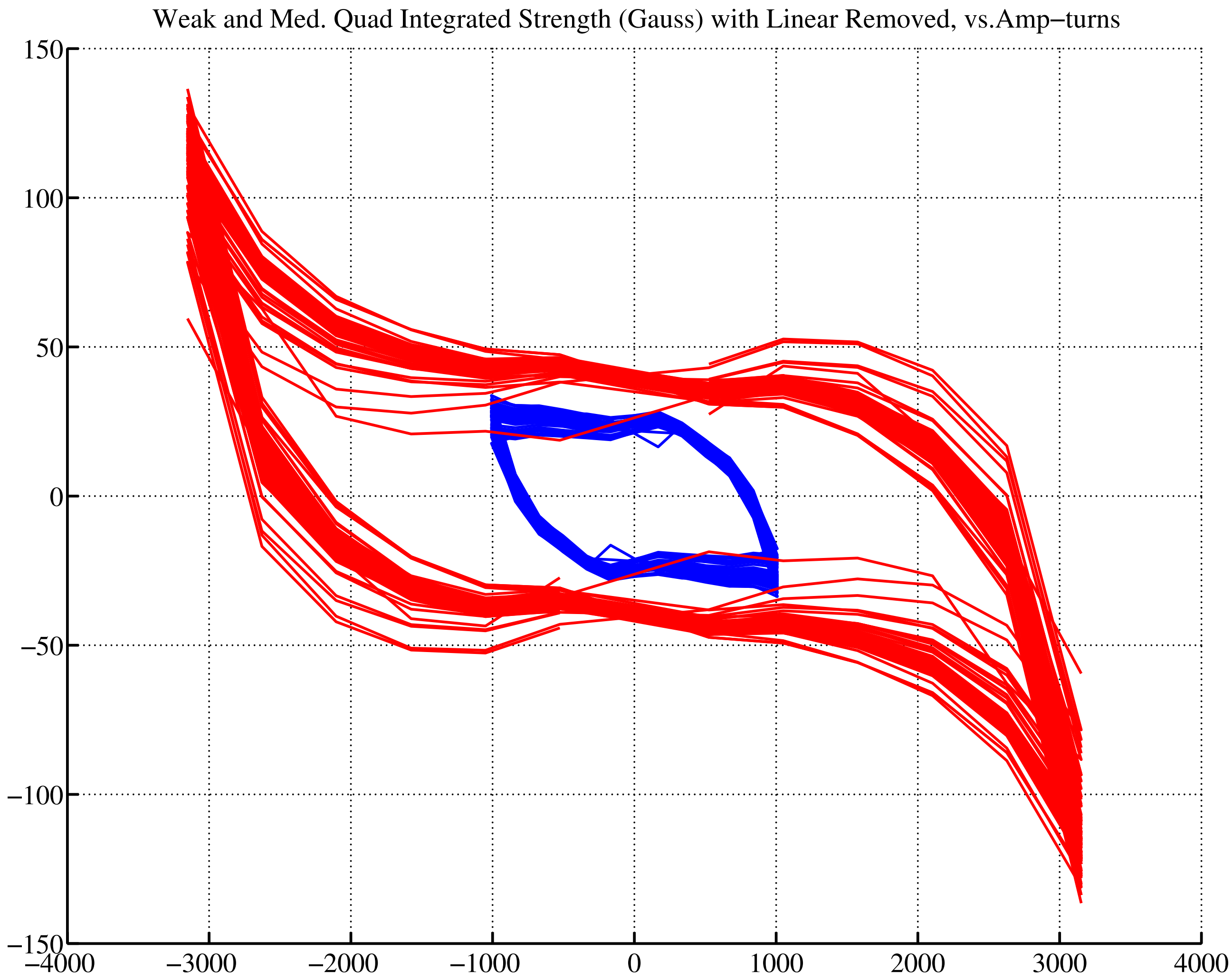

Figure 4: Weak (blue) and the Medium (red) calibration curves with fitted linear parts subtracted. The initial parts were omitted and the flipped curves ($S \to -S$, $I \to -I$ superposed to give the complete loops.

Calibration Curves

From this latter figure, one can see the extra remanent magnetization when going to the higher excitation of 3160 A-t: it is ± 40 Gauss, where the weak case of only going to 1008 A-t is, as we have seen, ± 25 Gauss.

If the excitation has not exceeded 3160 A-t (39 Amps), but one does not know the excitation history, then this represents the uncertainty in the integrated field. Further, we can fit the rest of the curve, which clearly nears saturation:

$$\frac{S}{\text{Gauss}} = 7215\,\tilde{I} - 100\,\tilde{I}^5 \pm 40 \text{ with } \tilde{I} = \frac{I}{39\,\text{A}} \tag{4}$$

But as with the weaks, we can fit the hysteresis curve to narrow the uncertainty.

$$\frac{S}{\text{Gauss}} = 42 + 7207\,\tilde{I} - 60\,\tilde{I}^5 - 0.55e^{5\tilde{I}} \pm 10 \tag{5}$$

As uncertainty, I now have ± 10 Gauss, but this reflects a rather large scatter that include significant outliers. If quads are carefully selected, this can be reduced, and the outliers relegated to roles where small uncertainty not required.

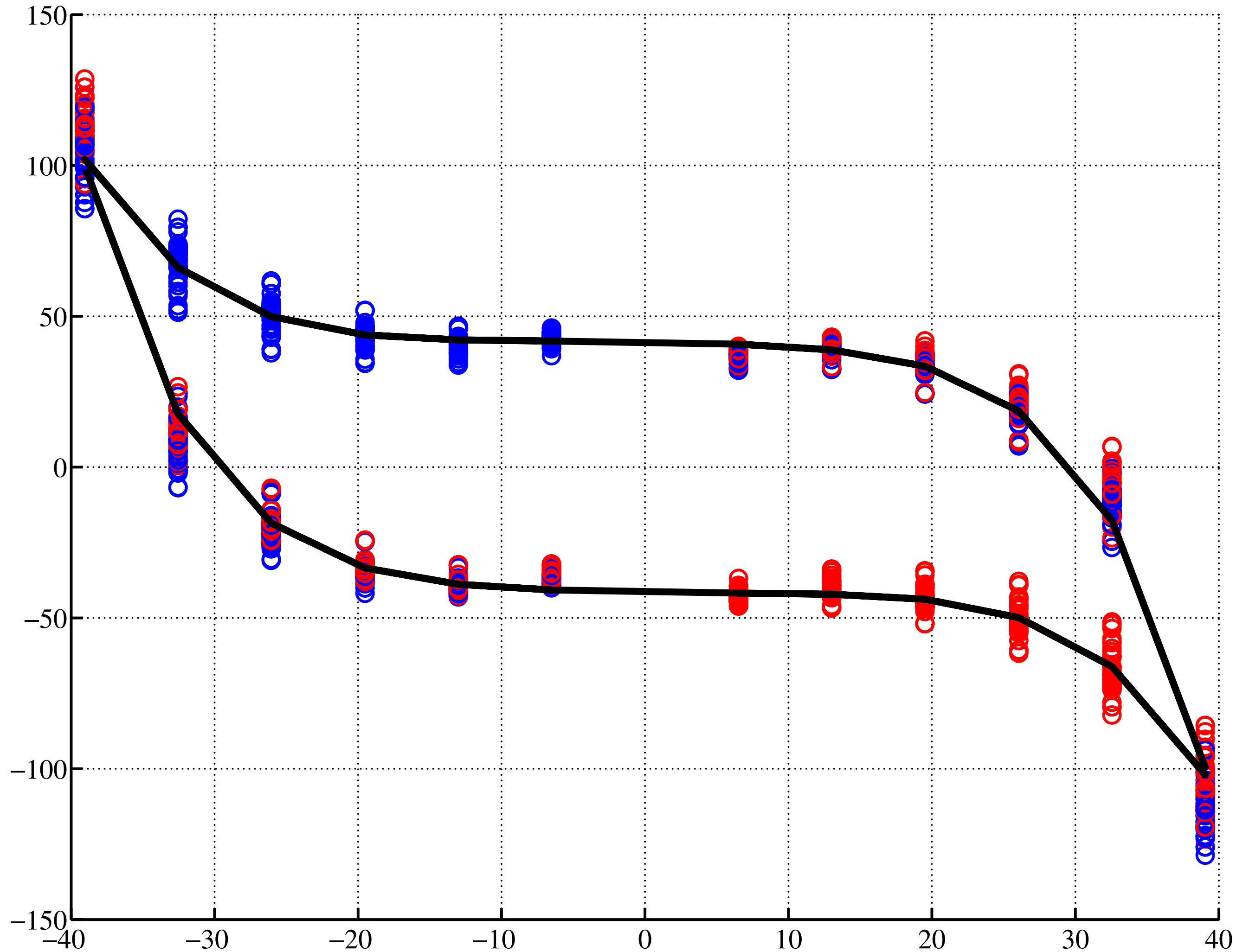

Figure 5: Integrated strength with linear part subtracted. Medium quad serial nos. 4, 5, 6, 8-14, 17, 18, 20-52, measured and negative of measured (blue and red resp.) along with (Black) Fitted function $S(\tilde{I})$ and $-S(-\tilde{I})$ eqn. 5 that follows the hysteresis curve.

Strong Quads

The Strong quads appear not to have been as carefully manufactured regarding steel and coil properties. Histogramming remanent field and peak field shows that there are 10 quads, serial numbers 9 thru 18, with well-matched properties: remanent integrated fields of $89 - 94$ Gauss, and at $I = 45$ A, strength $1.310 - 1.313$ T. The serial numbers 2 thru 8 clearly are from a different batch of steel, since their remanent strengths are very different at $69 - 72$ Gauss. Further, serial 5 and 6 must have coils with extra turns, since their $S(45\,\mathrm{A})$ is 1.342 T.

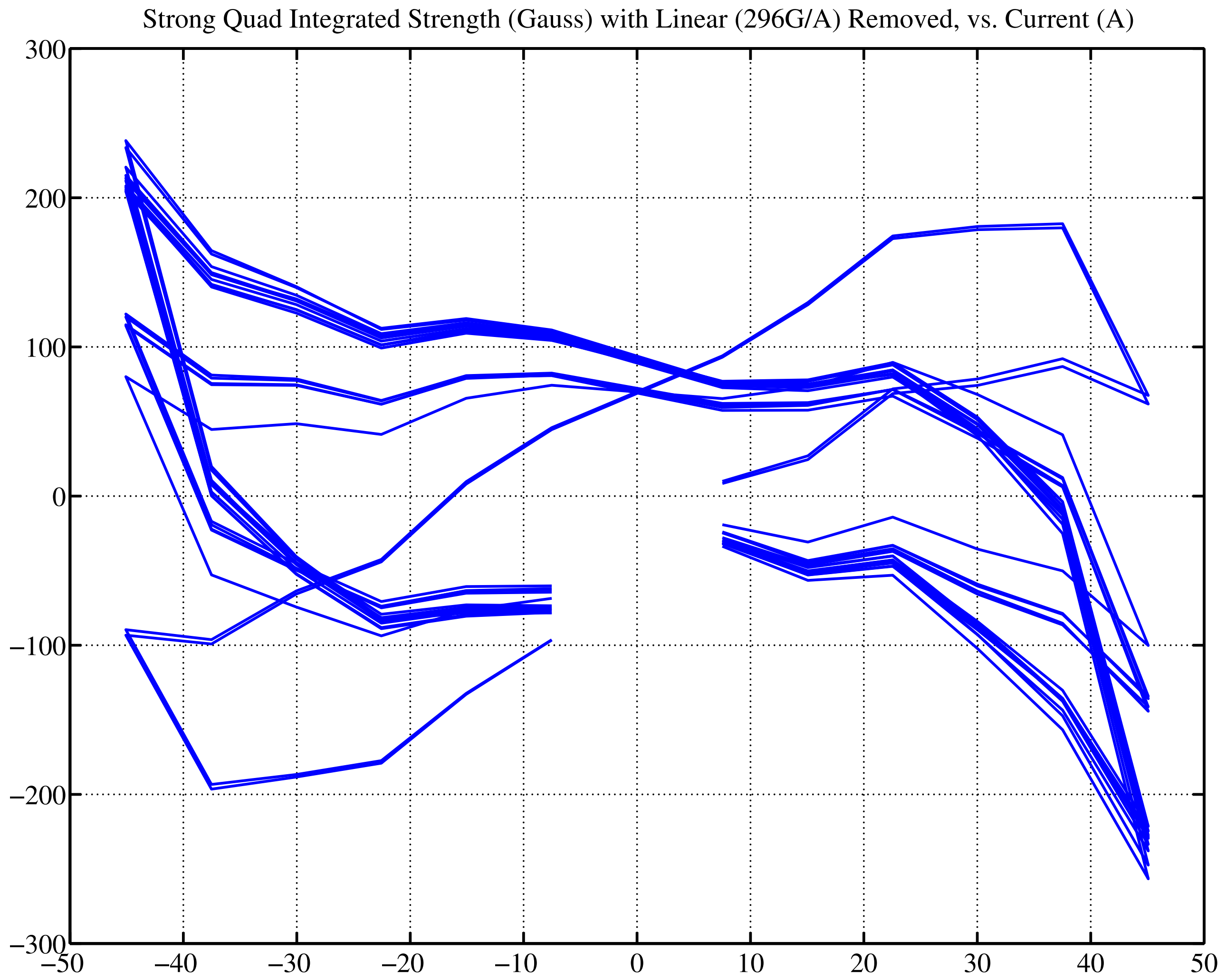

Figure 6: 17 strong quads' measured integrated strengths versus current, with linear part subtracted.

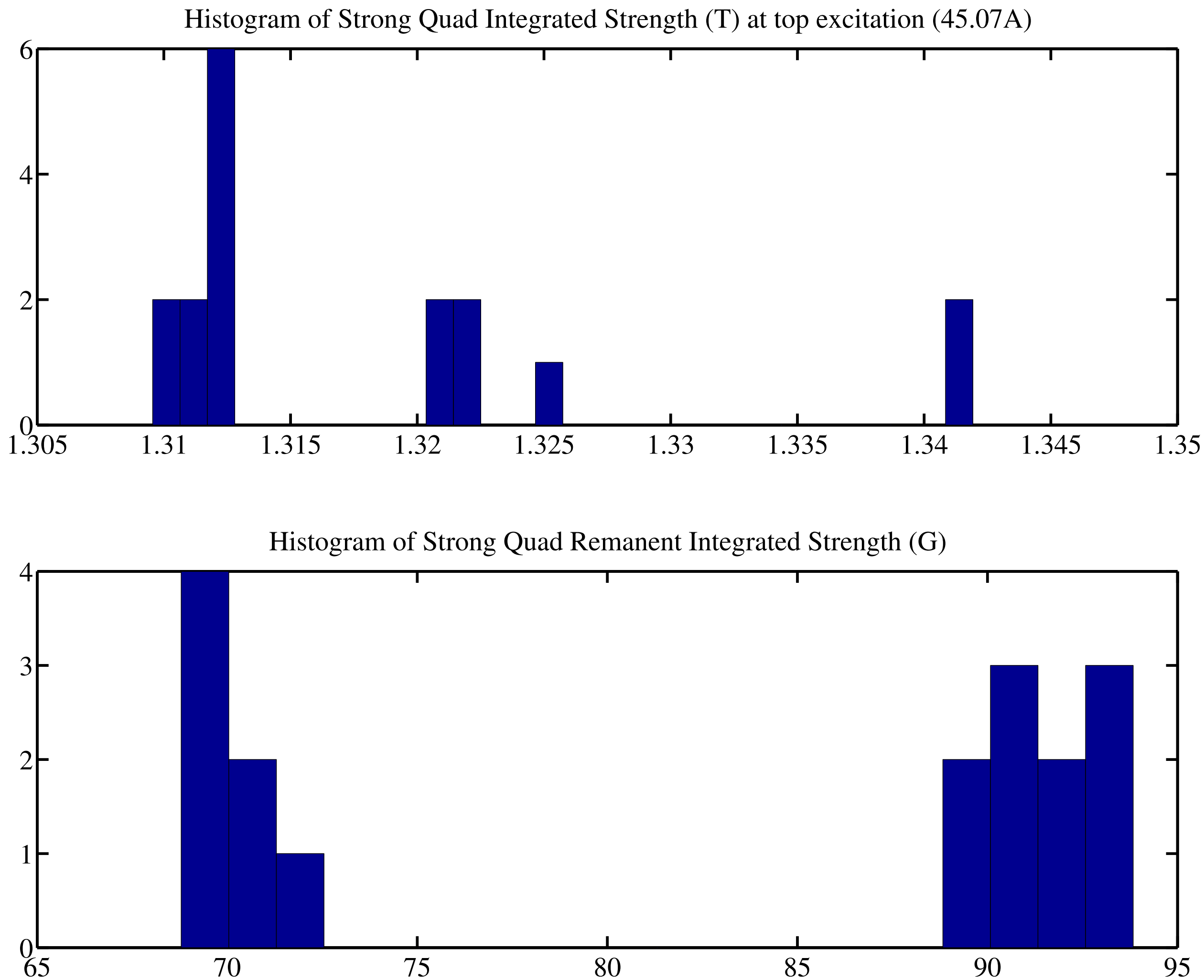

Figure 7: 17 strong quads' distribution of remanent field and field at top excitation.

Calibration curve

Choosing only the serial numbers 9 thru 18, as before, we fit the de-excitation curve to a fifth order (for saturation) plus exponential (for hysteretic effects). Here is the equation, followed by the plot.

$$\frac{S}{\text{Gauss}} = 97 + 13341\,\tilde{I} - 130\,\tilde{I}^5 - 0.5e^{6\tilde{I}} \pm 20 \text{ with } \tilde{I} = \frac{I}{45\,\text{A}} \tag{6}$$

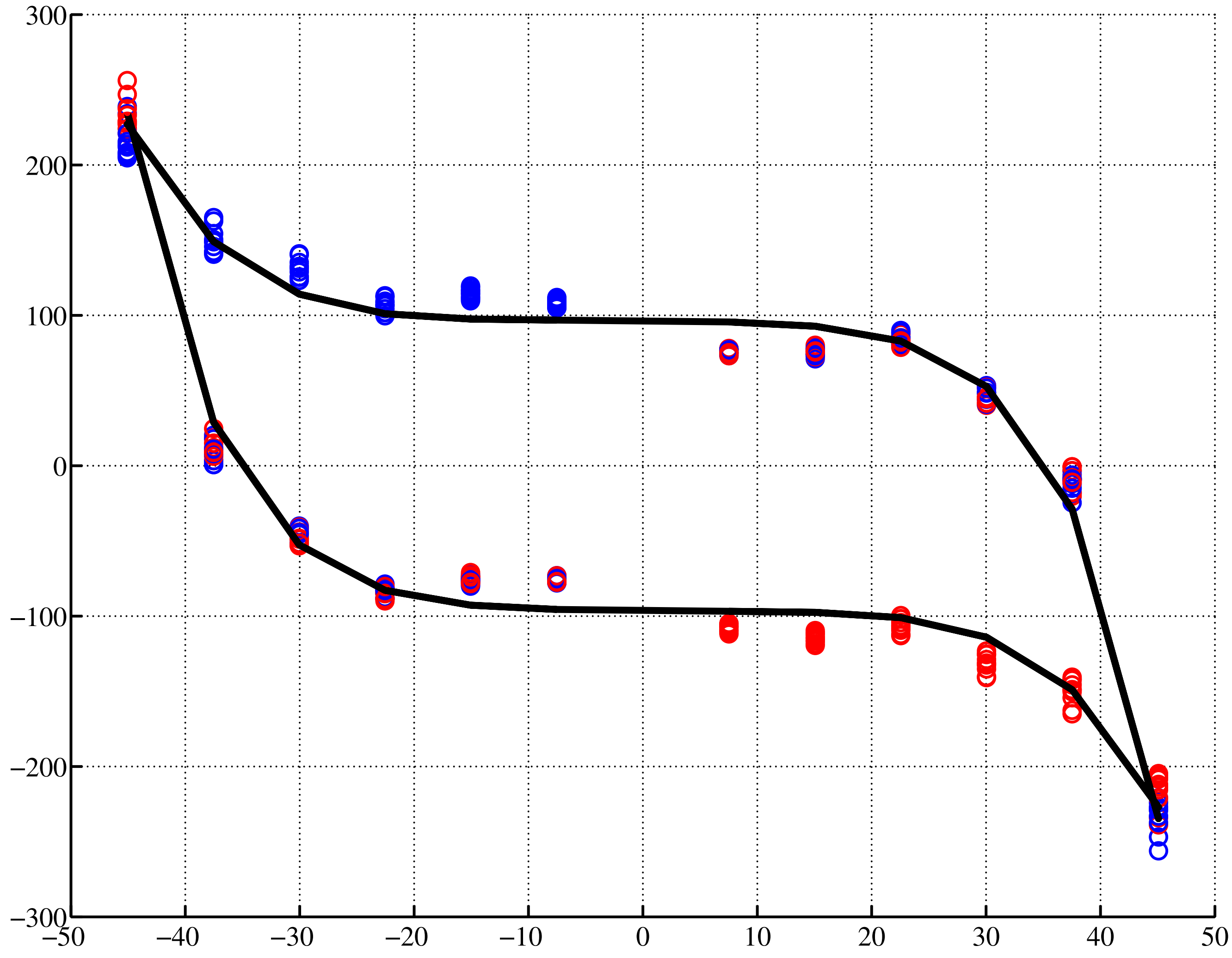

Figure 8: Integrated strength with linear part subtracted. 10 Strong quads: serial nos. 9-18, measured and negative of measured (blue and red resp.) along with fitted (black curve, eqn. 6).