SSCL-Preprint-290

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May 1993
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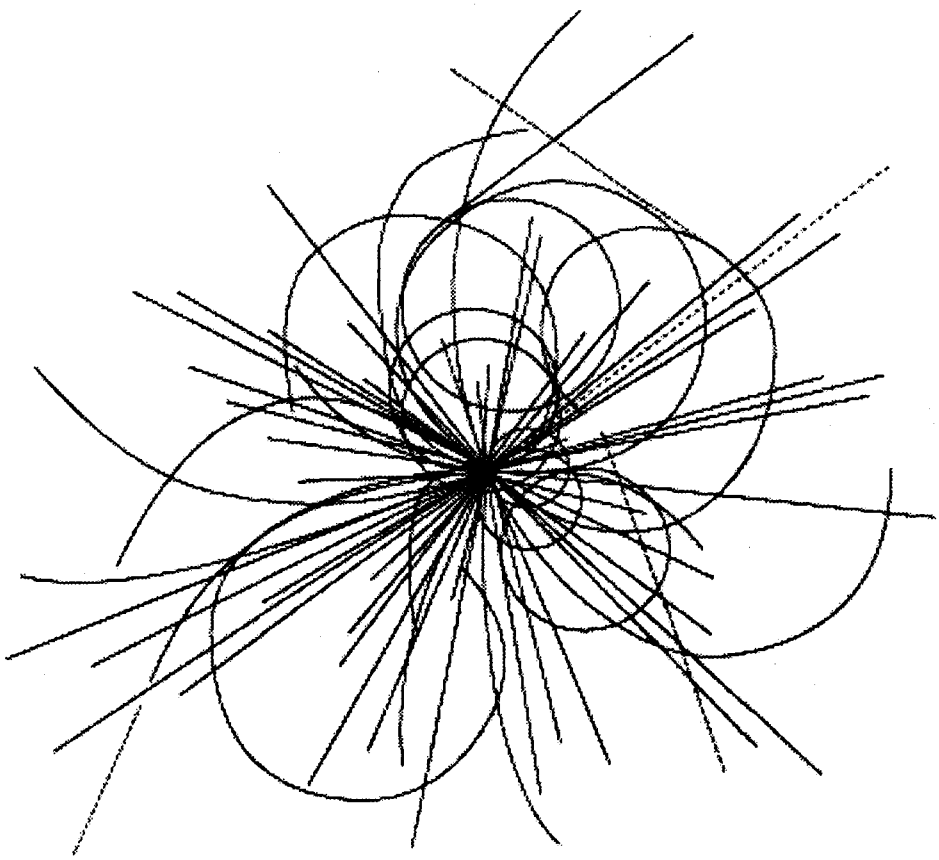

Superconducting Super Collider Laboratory

To be published in *Supercollider 5*

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May 1993

*Presented at the Fifth Annual International Symposium on the Super Collider, May 6–8, 1993 San Francisco, CA.
†Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

THE APPLICATION OF MOVING AVERAGE CONTROL CHARTS FOR EVALUATING MAGNETIC FIELD QUALITY ON AN INDIVIDUAL MAGNET BASIS

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INTRODUCTION

SSC Collider Dipole Magnet field quality specifications define limits of variation for the population mean (Systematic) and standard deviation (RMS deviation) of allowed and unallowed multipole coefficients generated by the full collection of dipole magnets throughout the Collider operating cycle. A fundamental Quality Control issue is how to determine the acceptability of individual magnets during production, in other words taken one at a time and compared to the population parameters. Provided that the normal distribution assumptions hold, the random variation of multipoles for individual magnets may be evaluated by comparing the measured results to +/- 3 x RMS tolerance, centered on the design nominal. To evaluate the local and cumulative systematic variation of the magnets against the distribution tolerance, individual magnet results need to be combined with others that come before it. This paper demonstrates a Statistical Quality Control method (the *Unweighted Moving Average* control chart) to evaluate individual magnet performance and process stability against population tolerances. The DESY/HERA Dipole cold skew quadrupole measurements for magnets in production order are used to evaluate non-stationarity of the mean over time for the cumulative set of magnets, as well as for a moving sample.

SKEW QUADRUPOLE RESULTS FOR ABB HERA DIPOLE MAGNETS

The HERA tolerance for the skew quadrupole at a reference radius (r_0) of 2.5 cm and 5000 A is +/- 4.0 x 10^{-4} units "maximum variation" and 1 x 10^{-4} units "standard deviation." [1] Skew quadrupole multipole (a_1, USA system) results for 214 HERA dipole magnets produced by Asea Brown Boveri AG, Mannheim, Germany (ABB) are shown in Table 1.

Table 1. Skew Quadrupole * Summary for 214 HERA Dipole Magnets (Producer: ABB)

Minimum	Maximum	Mean	σ	SEM **
-4.55	3.17	-0.0696	1.5897	0.10867

* units x 10^{-4}. ** SEM = Standard Error of the Mean = σ / sqrt (n). Data Source: DESY.

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ABB was one of two suppliers of dipole magnets for HERA. Due to publication limitations only the ABB portion of the dipole production will be discussed. It should also be noted that the HERA specification placed no "systematic" tolerance on multipoles.

The distribution of skew quadrupole results for the ABB magnets is assumed to be normal, for demonstration purposes, and is shown in Figure 1. The individual results by magnet production sequence (numbered by coil assembly date) are shown in Figure 2.

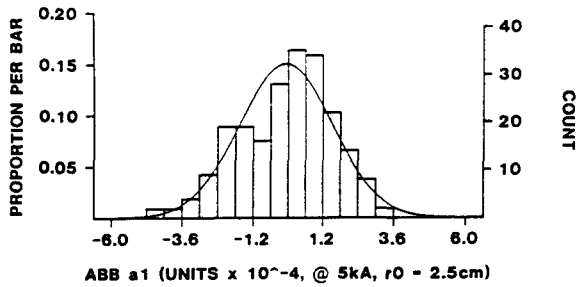

Figure 1. ABB a_1, Frequency Histogram of individual cold magnet results for 214 magnets.

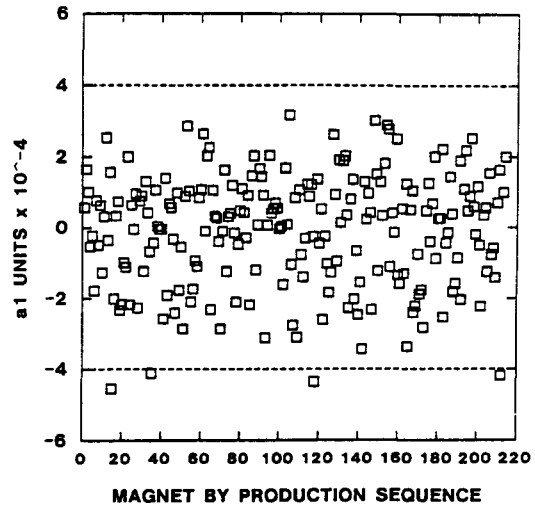

Figure 2. ABB a_1, individual results by magnet production sequence (ordered by coil assembly date).

The cumulative behavior of the sample mean and sample standard deviation every tenth magnet for an increasing size collection of the ABB dipole magnets is shown in Figures 3 and 4. The Standard Error (SEM) is included in Figure 3 to reflect the decreasing uncertainty of the mean with the increasing number of magnets averaged.

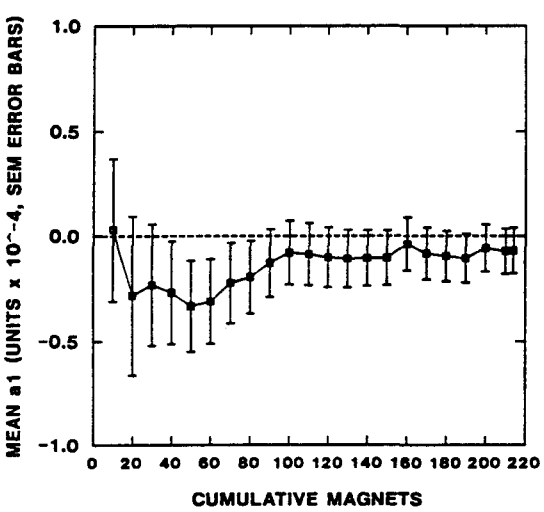

Figure 3. Variation of Mean Over Time, a_1 by cumulative number of magnets, with SEM bars.

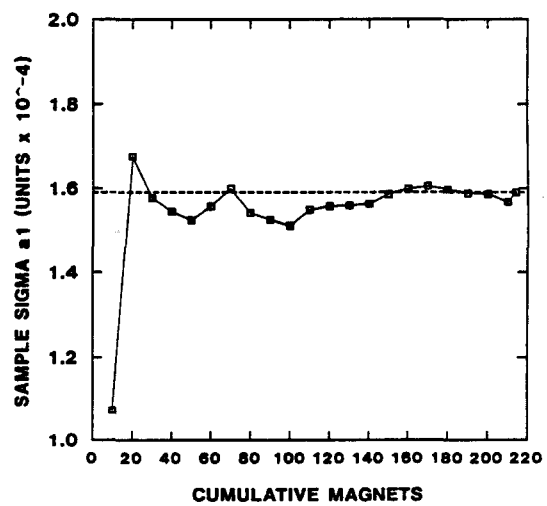

Figure 4. Variation of σ Over Time, standard deviation of a_1 by cumulative magnets.

THE UNWEIGHTED MOVING AVERAGE MODEL (UWMA)

A detailed description of the Unweighted Moving Average may be found in reference 2. The 3σ *Process Limits* for the UWMA are defined as:

$$UCL(M_t) = \mu + \frac{3\sigma}{\sqrt{nw}} \qquad LCL(M_t) = \mu - \frac{3\sigma}{\sqrt{nw}}$$

where M_t = the moving average at time t, w = moving average width or span at time t, n = sample size (for individual magnet evaluation, $n = 1$), and μ = population target mean of all measurements.

For the present application, nw is the number of magnets averaged. During the initial time period (for $t < w$) the control limits are wider than their final steady-state value due to the changing sample size (nw). For a collection of magnets $< w$, the average is computed with the current number of magnets observed. At "steady state" ($t > w$) the oldest magnet observation is dropped and the newest one added to M_t. Since t is incremented for each magnet observed, the influence of each magnet is evaluated as it is observed.

Figures 5 and 6 demonstrate the UWMA for ABB Skew Quadrupole data. In both examples the center is 0 (the target population average), σ (the population standard deviation) is fixed at 1 (the specification limit for σ). The moving average width grows as $w = t$ in Figure 5, and is fixed at $w = 10$ magnets in Figure 6. The data are in time order, based on coil collaring date. Note that the process limits vary with the number of magnets unless $t > w$.

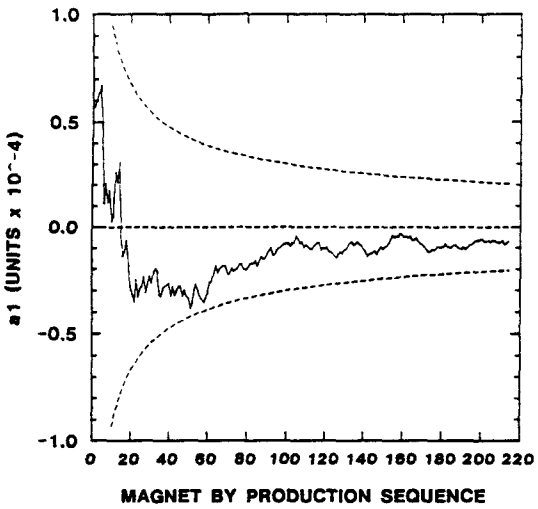

Figure 5. HERA a_1 UWMA for ABB Magnets ($w = t$, center = 0, σ = 1), with 3σ process limits for w = the cumulative number of magnets produced up to time t.

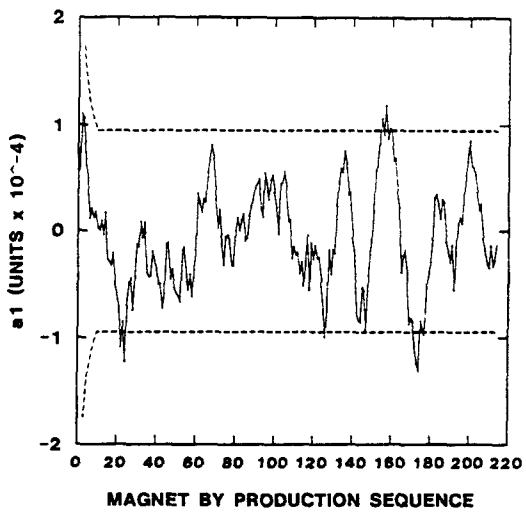

Figure 6. HERA a_1 UWMA for ABB Magnets (w = 10, center = 0, σ = 1), with 3σ process limits for w = a moving average of 10 magnets.

The non-stationary behavior of the process mean (systematic multipole) may be observed in the UWMA chart. The choice of the moving average width (w) has a dramatic influence on the output of the model. In Figure 6, relatively stable behavior is observed from magnet 20 to 120. Between magnet 120 and 220 some new source of variation appears to have entered the process as observed in the wide fluctuation of the process mean. Planned research with HERA ABB manufacturing data, which has recently become available to the SSCL MSD, will evaluate possible manufacturing causes for the observed multipole variation.

SENSITIVITY OF THE UWMA MODEL

The ability of a statistical quality control model to detect significant systematic change depends not only on the amount of variation in the process but also on risk probabilities that are tolerated when setting up the control system. The probability that an observation will be outside the statistical control limits and rejected when it is really from the same population and should be accepted is known as alpha risk (α, or producer's risk). For +/- 3σ limits, α = 0.0027 or 0.3%. The probability that an observation will be inside the control limits and *accepted* when it is really from another population and should be *rejected* is known as beta risk (β, or consumer's risk). Beta (β) depends on several factors including: sample size, population standard deviation, α, and distance of the alternate mean from the target mean. Table 2 shows various β probabilities for the ABB skew quadrupole data, assuming control limits are based on a target mean of 0, with a population standard deviation of 1.6 or 1, and α of 0.0027 (3σ control) or 0.05 (2σ control) and the process is off center at -0.07 units (the observed mean for ABB dipoles). Though not a requirement for ABB, the -0.07 unit systematic deviation from a center of 0 units is larger than the SSCL

systematic a_1 specification allowance of 0.04 units. In order to increase the probability of detecting an alternate mean (with the model control limits) β should be as small as possible. See reference 3 for more discussion of α and β risk and sample size using an SSC example.

Table 2. β Probabilities for Various UWMA Model Conditions.

	$\alpha = 0.0027,\ \sigma = 1.6$	$\alpha = 0.0027,\ \sigma = 1.0$	$\alpha = 0.05,\ \sigma = 1.0$
nw	β	β	β
10	0.997	0.997	0.945
50	0.996	0.994	0.924
500	0.980	0.932	0.674
1000	0.951	0.807	0.431
5000	0.500	0.385	0.002

THE EXPONENTIALLY WEIGHTED MOVING AVERAGE

An alternate method for monitoring systematic variation over time is the Exponentially Weighted Moving-Average (EWMA). In the EWMA a smaller weight is applied to older observations in the time series. The advantage of the EWMA is as a *forecasting* tool. The EWMA can be used not only to identify *when* but also by *how much* a process should be adjusted. [4]

CONCLUSION

The Unweighted Moving Average method provides a simple means of monitoring individual magnet multipole performance against population tolerances for systematic multipoles, from the "first" magnet made to the "last." The method also provides an indication of manufacturing process stability over time (for either the "cumulative" observations of all magnets up to the current time, or for a local moving width of observations). The careful selection of the moving average "width" can provide a useful tool for detecting the influence of variation in magnet components and tooling.

Through continued research and analysis of the magnet manufacturing data collected from SSC Prototype Magnets, as well as from the HERA ABB production experience, improved methods for monitoring systematic multipole variation in SSC superconducting magnets may be identified.

ACKNOWLEDGMENTS

S. Wolff, P. Gall, and H. Brueck. DESY, Hamburg, Germany.
Y. Zhao, A. Devred. SSCL, Dallas, Texas.
D. Bonmann. Asea Brown Boveri AG, Mannheim, Germany.
F. Eyβelein. Noell GmbH, Würzburg, Germany.

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4. ibid. Montgomery, pp. 279 ff.