IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

PRECISION MAGNETIC MEASUREMENTS BY THE FLOATING WIRE ANALOG TECHNIQUE

Michael I. Green, Charles G. Dols, Thomas F. Henderson and Donald H. Nelson*

ABSTRACT

Two SuperHILAC magnetic spectrometers were calibrated by means of current-carrying, floating wires. An "effective" radius-of-curvature as a function of single position measurements of magnetic-induction was determined with a probable error of ±0.02% over the range of rigidity: $0.3 \leq B\rho \leq 2.4$ (Tesla-meters). Employed in the calibrations were: optical detectors for determining wire position, an eddy-current "jiggler" for reducing pulley "stiction," a vacuum re-entrant tube for allowing calibration under spectrometer operating conditions, two-axis gradient correction coils for operating an NMR magnetometer in gradients of 70 Gauss/cm, a calculator program for facilitating data collection, and a computer program for data reduction and presentation.

INTRODUCTION

In the period July 1976 to June 1978, two LBL magnets ("Brutus" and "Fannie") were calibrated for use as energy spectrometers. Particle trajectories through the magnets were modeled with "Floating Wire Analogs." Data from the wire analogs were correlated with single-point magnetic-induction (B) measurements. Rigidity, p/q (where p is momentum and q is the charge of a particle), is expressed (for a specific trajectory) as a function of single-point magnetic induction measurements, B.

The Floating Wire/Charged Particle Analog

Under the proper conditions in a magnetic field, the path assumed by a flexible, current-carrying conductor, maintained under tension, is the analog of the path of a charged particle.[1-6]

The path of a weightless, flexible wire is identical to a particle path in the same magnetic field when

$$-T/i = p/q,$$

where: T = wire tension (newtons), i = wire current (amperes), p = particle momentum (kilogram meters/second), and q = particle charge (coulombs).

The Taming of Brutus

Given Brutus, an old C-type beam-line switching magnet, we were asked to build a spectrometer for investigating operating parameters of the SuperHILAC accelerator and for making precision beam energy measurements (±0.5%). A pair of 0.25 mm slits, separated by 2.73 m, defined a trajectory entering the magnet gap. A 0.5 mm slitted detector, 1.75 m down-beam from the magnet, accepted particles that had been deflected by approximately 16°.

Beams of a very narrow rigidity range are selected into the detector slit as a function of the magnetic field. Our goal was to calibrate this selection as a function of the magnetic induction measured at the single point occupied by our probe. To accomplish this, we used the floating wire analog and a Nuclear Magnetic Resonance (NMR) magnetometer.[7]

Some of the effects to be "tamed" in order to meet the specifications of the spectrometer were magnet history, air-current noise, pulley quality, and wire position detection. A programmable calculator was used to facilitate positioning the wire at the slit locations.

The Challenge of Fannie

After two years of successful use, poor Brutus was scheduled for retirement in response to changes in beamlines. Now Fannie, an old H-type, beam-line switching magnet challenged us.

The Fannie spectrometer design (see Fig. 1) included a pair of 0.4 mm slits separated by 1.22 m defining a beam trajectory. A 0.5 mm slitted detector, 2.03 m down-beam from the magnet center, accepted particles deflected approximately 42° by Fannie.

Because the new spectrometer design permitted variable entrance-slit position, we needed five times as many data sets as were collected during the calibration of Brutus. And the scheduled calendar time for Fannie's calibration was one-half that allowed for Brutus. Another challenge was no available location for the single point magnetic-field measurement in the uniform field region of the magnet.

THE FANNIE ATTACK PLAN

To calibrate Fannie we decided to use much of the Brutus system. We planned to improve the pulley system and to include the effect of vacuum during the calibration (see Atmospheric-Pressure Wire-Tunnel below).

For the single-point B-measurement, we chose a convenient point in the magnet gap where the gradient reached 0.7 T/m (70 G/cm). We planned to procure an NMR probe containing orthogonal gradient compensation coils.

During the Brutus calibration, wire positions were determined by ohmic contact with the floating wire. Although the reproducibility was good [±25μm (±0.001")], measurements were time-consuming and fatiguing. We decided to use "Measuring Microscopes" for determining wire position.

Measuring Microscopes

Three microscopes with 45° eyepieces and specially calibrated retical scales were used to measure wire position. Each microscope was mounted on a horizontal slide so that gross movements of the microscopes could be made and measured, using dial vernier-micrometers (Fig. 2).

Small movements of the wire were measured by observing wire position on the retical scale of the microscope. The measuring-microscope system and precision surveying established wire position with an absolute accuracy of ± 50 μm (± 0.002") with reproducibility and resolution of ± 10 μm.

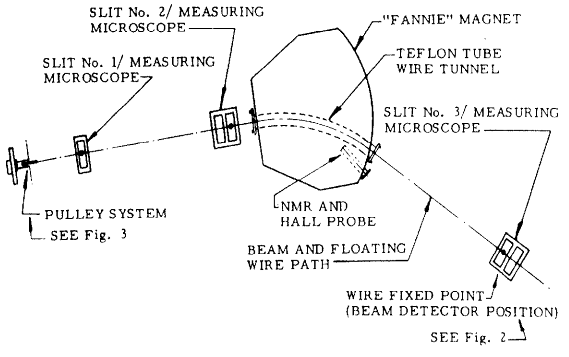

Fig. 1. Fannie Spectrometer Design

---

*Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720. This work was supported by the U.S. Department of Energy under contract No. W-7405-ENG-48.

0018-9499/79/0600-4003$00.75 © 1979 IEEE

Precision Pulley System

Typically, the pulley is the limiting factor in precision floating wire analog calibrations. Parameters to be determined are eccentricity, wobble, stiction (static friction), and balance. One of the less obvious effects is the perturbation of effective torque due to deformation of stranded wire going over the pulley. Figure 3 is a photograph of the pulley system.

Innovative Use of Stranded Wire

Stranded wire, due to its flexibility, is preferred over single-strand wire.[8] We used stranded copper wire (17 x 44) whose diameter was $\sim$0.25 mm. The problem of wire deformation on the pulley was eliminated by running nylon monofilament over the pulley and tying it to the stranded copper wire.

The Pulley Jiggler

The effect of pulley stiction was reduced in a simple way, without physical contact, by means of an electromagnetic weight "jiggler" (Fig. 3). The weight used to produce tension in the wire was a brass ring. A pair of electromagnets were located on the axis of the ring and were individually energized with pulses of alternating-current. The induced eddy-currents interacted with the field of the electromagnet to produce a repulsive force on the ring, which force is transmitted through the monofilament to the pulley. The corresponding small-amplitude oscillation of the pulley effectively eliminated the effect of bearing stiction, thus enabling achievement of high reproducibility.

Pulley Errors

The pulley was tested over a 360° range of angular orientations with the bearing load planned for the spectrometer calibration. Without the jiggler, the pulley would contribute a maximum of ±0.035% error in our results. The jiggler reduced the uncertainty to approximately ± 0.01%.

Single Point Magnetic Induction (B) Measurements

In both spectrometers, we studied the effect of extremes in magnet-history on the relationship between rigidity (R), magnet current, and single point magnetic induction measurements (B). While the establishing of a good correlation between magnet current and R require precise re-establishment of magnet-current-history effects, a good correlation (albeit non-linear) between B and R could be achieved with minimal restrictions on magnet-current sequences.

Single-point magnetic-measurements are related to rigidity by:

$$B\rho = R = p/q = -T/i;$$

ρ is an effective radius, which reflects the (variable) effects of field shape and implies an approximation to a uniform, "rectangular" field, and a constant radius of curvature. The remaining variables are defined above.

Nuclear Magnetic Resonance (NMR) Magnetometer

An NMR Magnetometer was chosen as the standard for the single-point magnetic-induction measurements. We are using a single-range, single-probe instrument with automatic signal searching and tracking over most of the

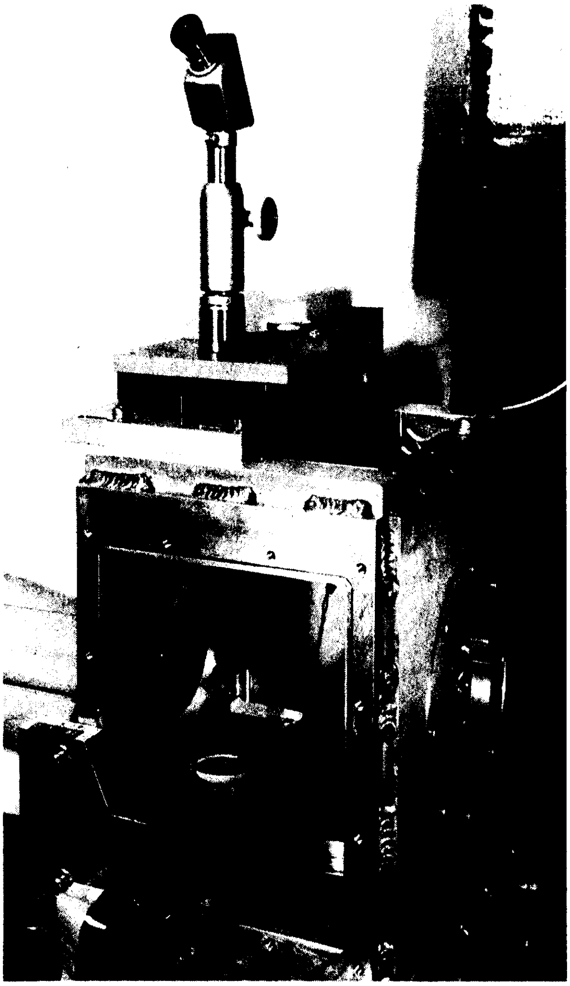

Fig. 2. Wire Fixed Point and Measuring Microscope

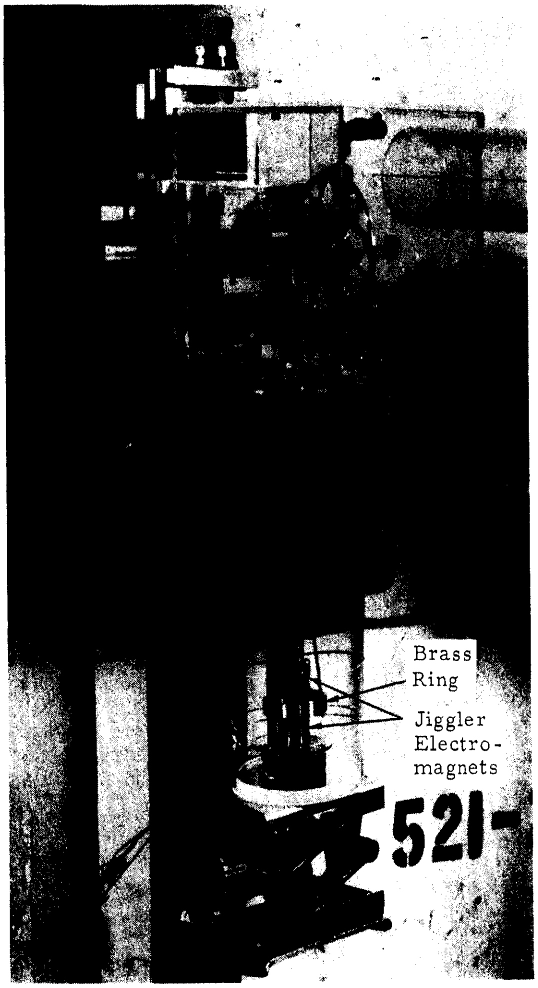

Fig. 3. Pulley System and "Jiggler"

range from 0.1 to 2.0 T. Its inherent accuracy is better than 10^{-6}; however, its operational accuracy is more like 10^{-5}. While an NMR ptobe is dedicated to and is semi-permanently mounted within the spectrometer, the expensive control unit is available for intra-laboratory use with other probes.

NMR Gradient Coils

Because the options for positioning the NMR probe were limited, it is located at a point in the magnet where the gradient, ∇B_Z, is relatively high: 0.7 T/m (70 G/cm). The NMR sample, in fact, operates in a relatively homogeneous field because the field-gradient is compensated by two independent orthogonal pairs of gradient correction coils, which were designed into the probe structure.

Hall-Effect Probe

When the high precision NMR measurement is not required, a Hall-probe mounted with the NMR probe is used. The reproducibility of the Hall-probe system is better than ±0.3% and approaches ±0.1% when extreme care is taken.

Atmospheric-Pressure Wire-Tunnel

A teflon tube was installed through the vacuum tank of the "Fannie" magnet. This tube was bent to approximate the wire path through the magnet, and during calibration, the wire was floated through the tube. Each end of the tube was fitted with a sliding vacuum seal and adjusting screws. Adjustments of the screws changed the shape of the tube to accommodate the path of the floating wire. The floating wire was at atmospheric pressure throughout, while the magnet pole faces were at vacuum. Thus, both the magnetic and air-pressure forces (and deflections) during calibration equalled spectrometer operating conditions.

Iterative Calculator Program

To facilitate determination of the exact wire current and pulley position, we used a card-programmable, printing calculator. Our algorithm used wire-position data corresponding to values of wire current and pulley position to predict improved values. Usually, within 2 to 3 iterations, the wire was within 0.1 mm of the slit-center positions.

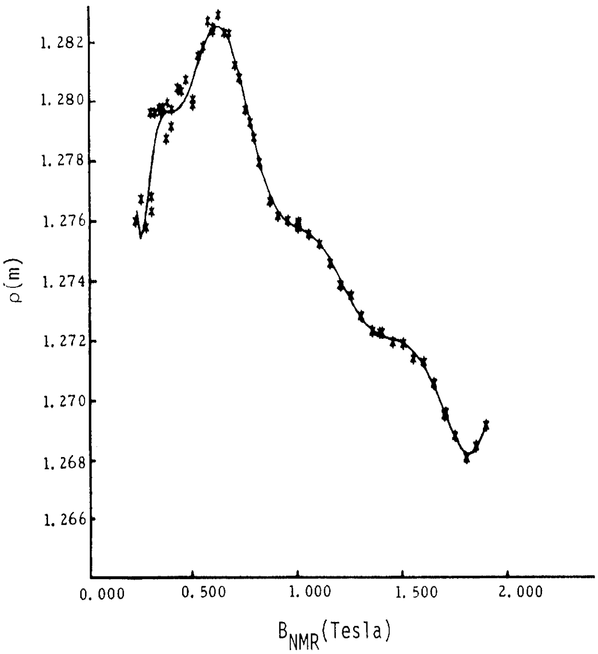

Fig. 4. "Effective" Radius of Curvature vs. B_{NMR} 13 Degree Polynomial Fit

RESULTS

Except for the pulley, all instruments were calibrated to better than 0.01%. To minimize bias in the data-acquisition procedure, data were first collected over the entire magnetic field range at 0.1 T intervals. Then intermediate data were collected at the 0.05 T intervals and finally, at 0.025 T intervals.

Raw calibration data were reduced with the aid of a small computer and a program entitled, "Polynomial Regression Evaluation." Preliminary results of the Fannie calibration were summarized in an Engineering Note to enable the SuperHILAC facility to test and to use the spectrometer.[9]

Figure 4 is a representative plot of our results. We have plotted "effective" radius of curvature (ρ) versus single-point magnetic-induction measurements, B_{NMR}, for a single trajectory over the range $0.22 < B_{NMR} < 1.9$ T.

The solid line is the least-squares fit of a 13 degree polynomial. The fit of the polynomial is generally better than 0.02% above 0.51 T. The scatter in the data below 0.51 T resulted from non-reproducible physical motion of the magnet pole pieces with respect to each other (accompanied by a POP! loud enough to wake up the data takers).

ACKNOWLEDGMENTS

The authors' appreciation goes to Frank Selph for his encouragement and financial support. For the enthusiastic use of their talents, we are also indebted to E.A. Cyr for the electrical set-up, to H.E. (Sam) Ketchum and R.W. Sorensen for tuning the magnet power supply and setting up the NMR gradient coil power, to R.G. Barry for calibration of the DVM, to R.N. Wood for calibration of the shunt, to W.R. Olthoff and W.J. Elwood for mechanical set-up and optical tooling, to J.C. Hodges and S.J. Klingler for cleaning and tuning the pulley, to J.A. Borde for calibrating the weight and to J.L. Moore for photography. For their continued patience we are indebted to the following data takers: L.J. Besse, R.M. Johnson, J.G. Kalnins, B.T. Leemann, F.B. Selph, J.E. Smith, C. Timossi, and M.D. Wolfe.

REFERENCES

1. O. Chamberlain, "Optics of High-Energy Beams," Ann. Rev. Nucl. Sci. 10, 180, 1960.
2. G.R. Lambertson, "Use of Wire Loop in Locating the Orbital Surface of a Cyclotron Field," Lawrence Berkeley Laboratory Report UCRL 3366, March 1975.
3. U. Vogel, "'Floating Wire' Technique for Testing Magnetic Lenses," Rev. Sci. Inst. 36, No. 2, 188, February 1965.
4. C.G. Dols, M.I. Green, D.H. Nelson, "The 'Floating Wire' Analog of Particle Motion in a Magnetic Field," Lawrence Berkeley Laboratory Engineering Note MT-277, March 1979.
5. S. Ramo, J.R. Whinnery, T. Van Duzer, Fields and Waves in Communications Electronics, John Wiley and Son, Inc., N.Y., p. 106, 1967.
6. Reference Data for Radio Engineers, Howard W. Sams & Co., Inc. (ITT), Sixth Edition, p. 48-18, 1975.
7. D.H. Nelson, M.I. Green, "Floating Wire Calibration of Hilac Analyzer Magnet, Brutus," Lawrence Berkeley Laboratory Engineering Note MT-257, August 23, 1976.
8. G.R. Lambertson, "Tests of a Flexible Wire for Particle Trajectory Studies," Lawrence Berkeley Laboratory Report UCID 647 (MT-41A), Revised 1961.
9. M.I. Green, "'Fannie' Wire Orbit Measurements - Preliminary Report," Lawrence Berkeley Laboratory Engineering Note MT-270, September 25, 1978.