MECHANICAL EQUIPMENT FOR MAGNET MEASUREMENT AND ALIGNMENT

*A. Harvey**)

Stanford Linear Accelerator Center, Stanford, CA, USA

Abstract

The mechanical equipment for measuring and aligning (or fiducializing) magnets is described by reference to devices designed and built by a number of laboratories. Some of these are now available commercially. The descriptions are supplemented by a list of representative sources of hardware.

1. INTRODUCTION

There are several requirements common to any magnetic measuring and alignment equipment:

i) positioning the magnetic field sensor with respect to the magnet;

ii) determining the characteristics of the magnetic field indicating uniformity, orientation, and boundaries; and

iii) providing alignment references to set the magnet in its required position—the process of fiducialization. These references have to be accessible when the magnet is in its final position.

This paper categorizes equipment generally into one of two kinds:

◊ *Universal*, or general purpose, measuring machines, such as those designed for measuring (a) dipoles, (b) quadrupoles, or (c) a combination of dipoles, quadrupoles and other magnets. (There is some commercial availability of such devices.)

◊ *Special purpose* measuring machines, such as those required:

(a) as mappers for cyclotron magnets,

(b) to measure size extremes (quadrupoles can be found with bores ranging from 1.25 m to 10 mm, and there are proposals to go smaller), and

(c) for the magnets for large synchrotrons (the Tevatron at Fermilab; Hera at DESY; the SSC), characterized by a long, small bore, and superconducting to boot.

Mechanical equipment will be described by examples from each of these categories, with references for more detailed descriptions and a compilation of sources that is not by any means exhaustive, but will give at least one supplier for each of the components. Note that these suppliers are often very helpful in explaining the choices that need to be made in specifying their products.

---

* Work supported by Department of Energy contract DE-AC03-76SF00515.

2. GENERAL PURPOSE MACHINES

2.1 Three-axis sensor positioner at TRIUMF, Vancouver, Canada [1]

This device is illustrated in Fig. 1. Each of the three orthogonal axes has a pair of support shafts with linear ball bearings (e) (see list of hardware sources in Section 5). The carriage on each axis is driven by a ball screw (d), whose shaft is rotated by a stepping motor (g). Calibration is in the inch–pound system, so it has been arranged to move 0.001 inch (25 μm) per pulse to the stepping motor. Limit switches are provided to set range and to prevent over-travel, and a mechanical counter provides for reset if the electrical count record is lost.

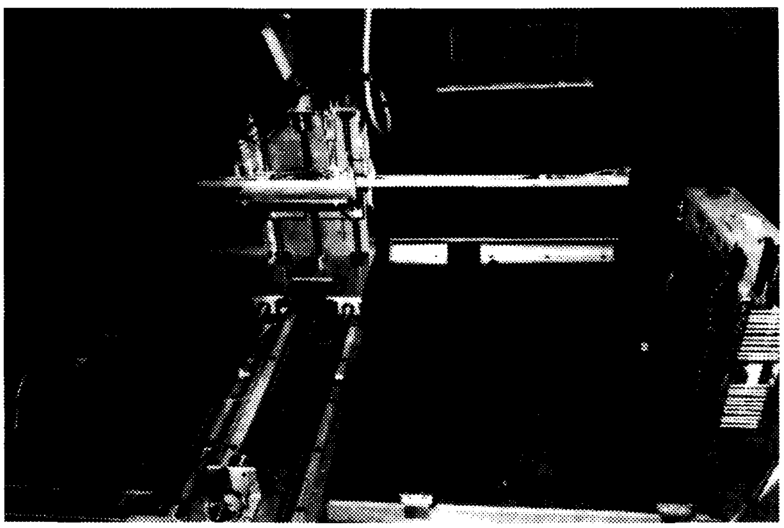

Fig. 1 TRIUMF three-axis probe positioner.

The sensor support boom is fixed, giving constant droop (in fact, for heavier sensors, it can be provided with an outboard bearing on a slaved table).

Sensors in use with this positioner include Hall probes (h), NMR probes and flip-coil arrays.

It is worth noting that manufacturers of some of the components used here, (e) (s), can supply complete three-axis positioning assemblies, with drive motors and position read out, ready for the user's computer interface—they have been developed for manufacturing automation applications.

2.2 Six-degree-of-freedom machine at GSI, Darmstadt, Germany

2.2.1 Design criteria

This system has six degrees of freedom, three translations and three rotations. The probe head is mounted at the end of a long probe arm. In order to minimize the oscillations of this arm, it is absolutely necessary to reduce any friction as much as possible, so only air bearings and air-bearing slide shoes are used. A summary of the design parameters is given in Table 1.

Table 1
Design parameters of the magnet measuring machine

Linear scan ranges (mm)	2700	1000	1000
Resolution	1	1	1
Rotation around axis (degree)	360	±100	+30
Resolution (mrad)	—	0.02	—
Dimension granite table (m)	3.6	—	1.5
Overall dimension machine (m)	4.	3.0	2.5
Weight (tons)		6	
Maximum length of probe arm (m)		4.0	

The complete system is shown in Fig. 2. This system is available commercially (k) and has four main parts:

◊ *The three-dimensional measuring machine itself.* This consists of a large granite table on a support subframe, two longitudinal slideways for the x–direction (horizontal), and one each for the y–direction (vertical) and the z–direction (orthogonal), respectively. The mechanical parts are driven on air-bearing shoes by motors using a continuous multiple steel band. The whole machine can be moved either by crane or air cushions.

◊ *The long probe arm.* Three different long cylinders that fit into each other. They are either bonded together or can move relative to each other like a telescope. Use carbon fiber epoxy, because of its high Young's modulus and low weight.

◊ *The probe head.* Three Hall probes (i) are mounted orthogonal to each other. The probe head is temperature stabilized better than 0.1 degree and calibrated against an NMR. The orientation of the probe head can be determined relative to the axis of a mirror in front of the probe by autocollimation. The internal direction cosines of the probe are measured with a precision of better than 1 part in 10000, separately.

◊ *The freely programmable motor control system.* Uses a commercially available modular motor control system for six servo motors. It was very important to machine the mechanical parts of the drive system carefully in order to avoid regulation problems of the control system. The software package allows master/slave operation, linear and circular interpolation, measurements *on the fly*, and so on.

2.2.2 Tests

The measuring machine was tested in three ways:

◊ Mechanically by electronic level meters. The maximum deviation of the flatness of the table was 8 μm, the slidways were straight within 4 μm. The three axes are orthogonal to better than 0.01 mrad.

◊ Optically by autocollimation using two mirrors, one attached to the vertical slideway and the other in front of the probe. Moving with a speed of 2 cm/s along the x-axis, the maximum angular deviations were 0.02 and 0.08 mrad, respectively—the latter value includes the effect of the vibrations of the long probe arm.

◊ By magnetic measurements. These data confirmed the results of the optical measurements.

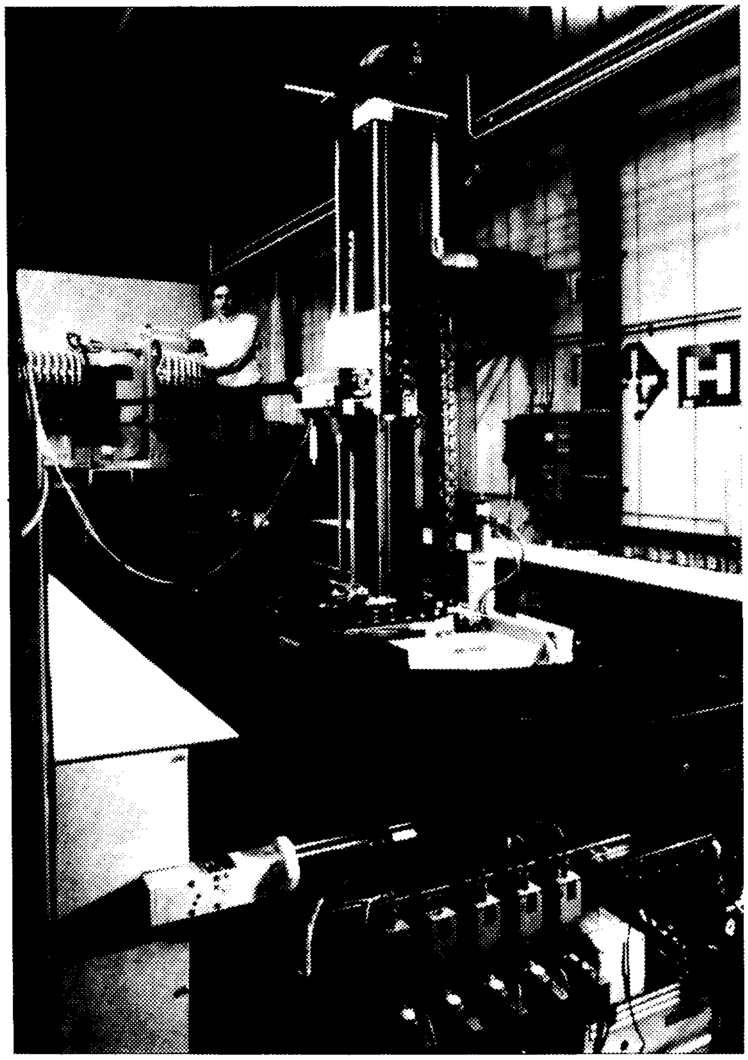

Fig. 2 GSI, Darmstadt, six-degree-of-freedom measuring machine.

2.3 Quadrupole measurement

A commercial company (l) makes two models of quadrupole measuring machines. One model is patterned after a GSI design of rotating-coil equipment, with manual positioning of the magnet to align its magnetic axis with the coil axis of rotation. A spectrum analyzer (c) on the coil output can be used to measure the harmonics.

The second model is like the machine CERN developed for the LEP quadrupoles and sextupoles [2]. It has automatic adjustment of the magnetic axis to the coil axis, to an accuracy of 30 μm; and provision for setting external fiducials on the magnet for alignment. All measurements are taken automatically, under the control of a microcomputer, which also sets the power supply. Features of the design include air-bearings for the coil; a dc motor drive with an angular encoder, and an integrator on the coil output. Figure 3 shows the equipment layout, and Fig. 4 shows the components.

2.3.1 Magnet positioning system

When mounted on the bench, the magnet can be moved by means of five stepping motors, with corresponding gears and power supplies. Horizontal and vertical translation and

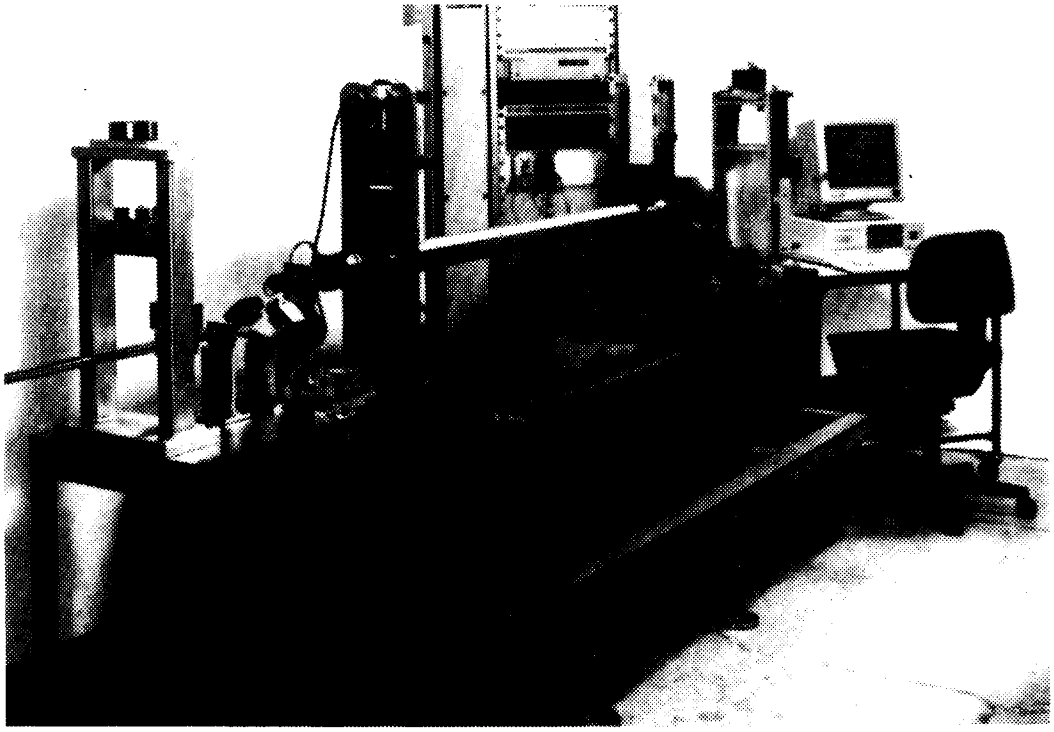

Fig. 3 Danfysik equipment layout

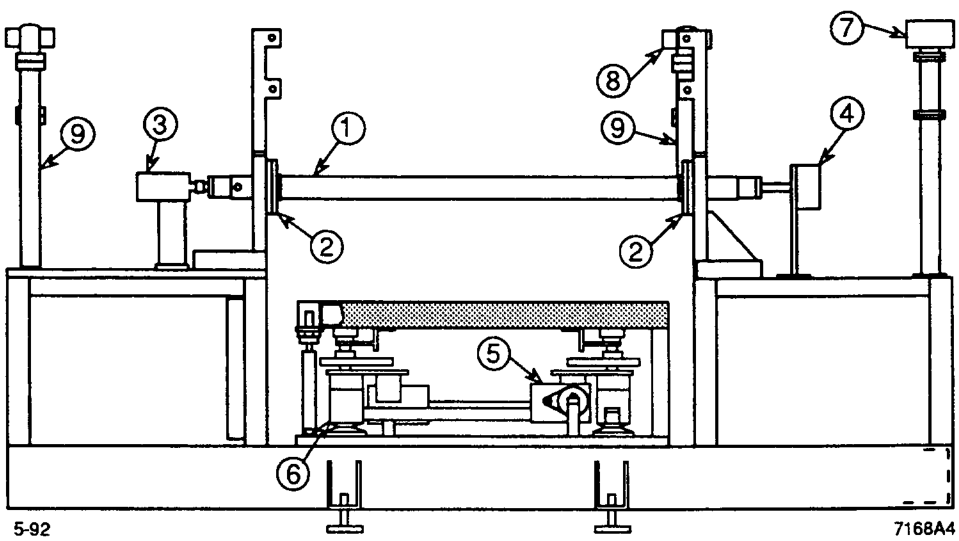

Fig. 4 Side view of measurement bench. Rotating coil assembly consisting of measurement cylinder (1), air bearings (2), DC motor (3), and angular encoder (4). Magnet positioning system consisting of magnet support platform, horizontal movement gears and motors (5), vertical movement gears (mounted on air cushions) and motors (6). Alignment system consisting of laser (7), photo detector with Taylor Hobson ball (8), and calibration supports (9).

rotation around three different axes are possible by simultaneous operation of two or three motors. During horizontal movements, the magnet is supported on four air cushions to minimize the friction. The resolution of the movements is approximately 1 μm for horizontal and 0.5 μm for the vertical movements. Position read out for each axis is provided by linear position potentiometers.

2.3.2 Alignment system

The alignment system consists of a laser, a position sensitive light detector (resolution ± 0.01 mm) mounted in a Taylor Hobson ball, and two electronic inclinometers (sensitivity 0.02 mrad). A calibration device is provided for initial alignment and maintenance checks of the laser. The alignment system is used for prealignment of the magnet before measurement and for final positioning of alignment targets on the magnet yoke.

2.3.3 Control system and software

The control system is designed to control the measurement sequence, and to provide information to the operator when his operations are controlled by the microprocessor in the G64 crate, which is connected to the RS232C serial interface of the PC. The G64 crate contains electronic modules for magnet positioning, magnet measurements, and alignment system. The microprocessor receives simple instructions and data from the PC, initiating a series of actions, returns data to the PC and acknowledges that the task has been performed. The PC controls the overall magnet positioning, alignment, and measurement procedures. It analyzes, displays, and sorts the data. Furthermore, via the IEEE48 bus, it controls the (optional) magnet power supply, and sets and reads the magnet current from the Ultrastab Current Transducer.

A typical measurement sequence will be the following:

1. Mounting of the magnet, connection of current cables and water cooling—a manual task.
2. Prealignment in order to be able to insert measuring coil, using inclinometer, laser and photo detector positioned on coarsely mounted target holders. Position reading and motor movements are automatic.
3. Magnetic centering performed by consecutive dipole field measurements and motor movements—performed fully automatically.
4. Measurement of main harmonic and higher order harmonics. Performed by one clockwise and one counterclockwise rotation of the coil. Data is automatically transferred to PC, analyzed, displayed, and stored.
5. Mounting of target holders and level mark in their fixed position using inclinometers, laser beam, and photodetector—a manual task.

2.3.4 Overall specifications

Relative accuracy of integrated main harmonic	$\pm 3 \times 10^{-4}$
Angular phase absolute accuracy	± 0.2 mrad
Lateral positioning of magnetic center with respect to rotation axis	± 0.03 mm
Positioning accuracy of alignment targets with respect to coil axis	± 0.03 mm
Accuracy of ratio between integrated field of a multipole component and the main component at the major coil radius	$\pm 3 \times 10^{-4}$

3. SPECIAL PURPOSE MACHINES

3.1 Cyclotrons

Everyone who builds a cyclotron has to build a magnet-measuring machine to match. Examples are the flip-coil arrays that were used at TRIUMF in Vancouver, BC, Canada, and the Hall probe (i) positioner at PSI, Villigen, Switzerland. This latter is probably unique in that it was duplicated for a similar cyclotron built in South Africa: Figure 5 shows the apparatus, and Fig. 6 shows it in place in the cyclotron.

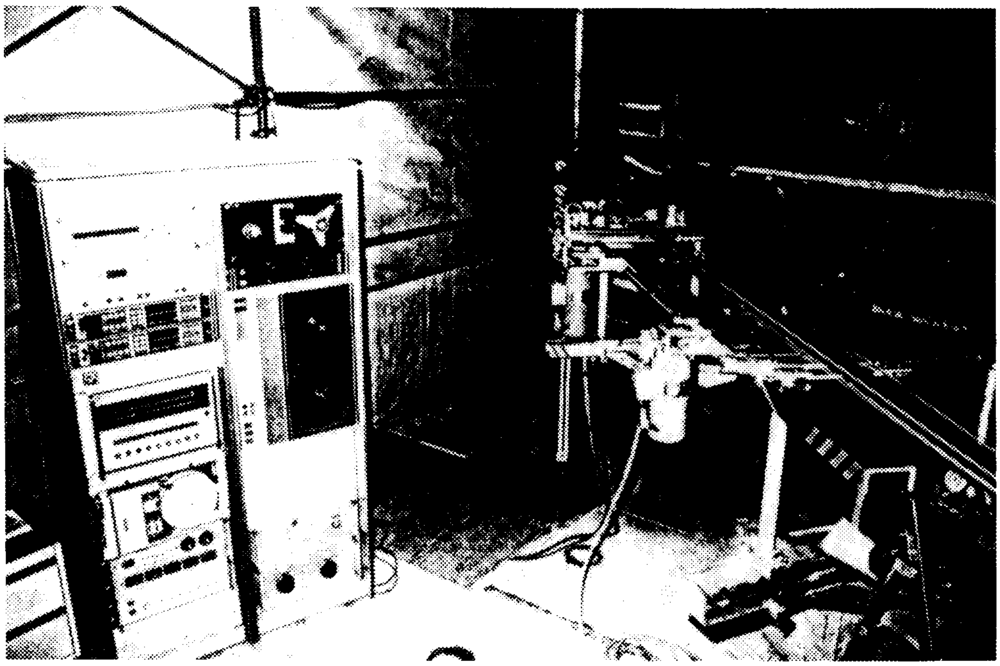

Fig. 5 PSI (SIN) Villigen: Hall-probe positioner

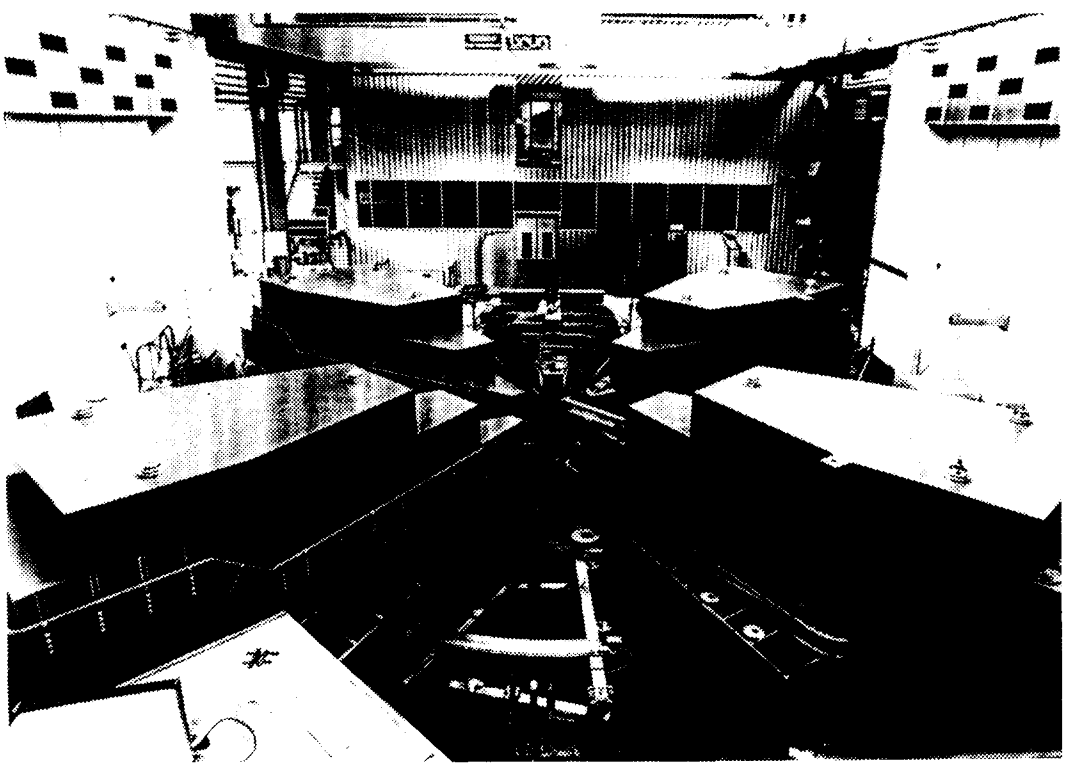

Fig. 6 PSI (SIN) Villigen: Hall-probe positioner in place in cyclotron

3.2 Size extremes

There are examples at Los Alamos National Laboratory, Los Alamos, NM, USA, of quadrupole permanent magnets as large as 1.25 m bore (see Fig. 7) and as small as 10 mm bore (see Fig. 8). The measuring coil for the large quad is made from G–10 epoxy fiberglass, and has a long settling time because of its inertia. Standard angular encoders (g), or synchro resolvers (r), are used for read out. Consideration is also being given to using piezo-resistive accelerometers for angular read out, since silicon micro-machining now makes these quite economical components (a,b). In the case of the small quad, the coil is made by printed-circuit techniques on a fused quartz substrate (f).

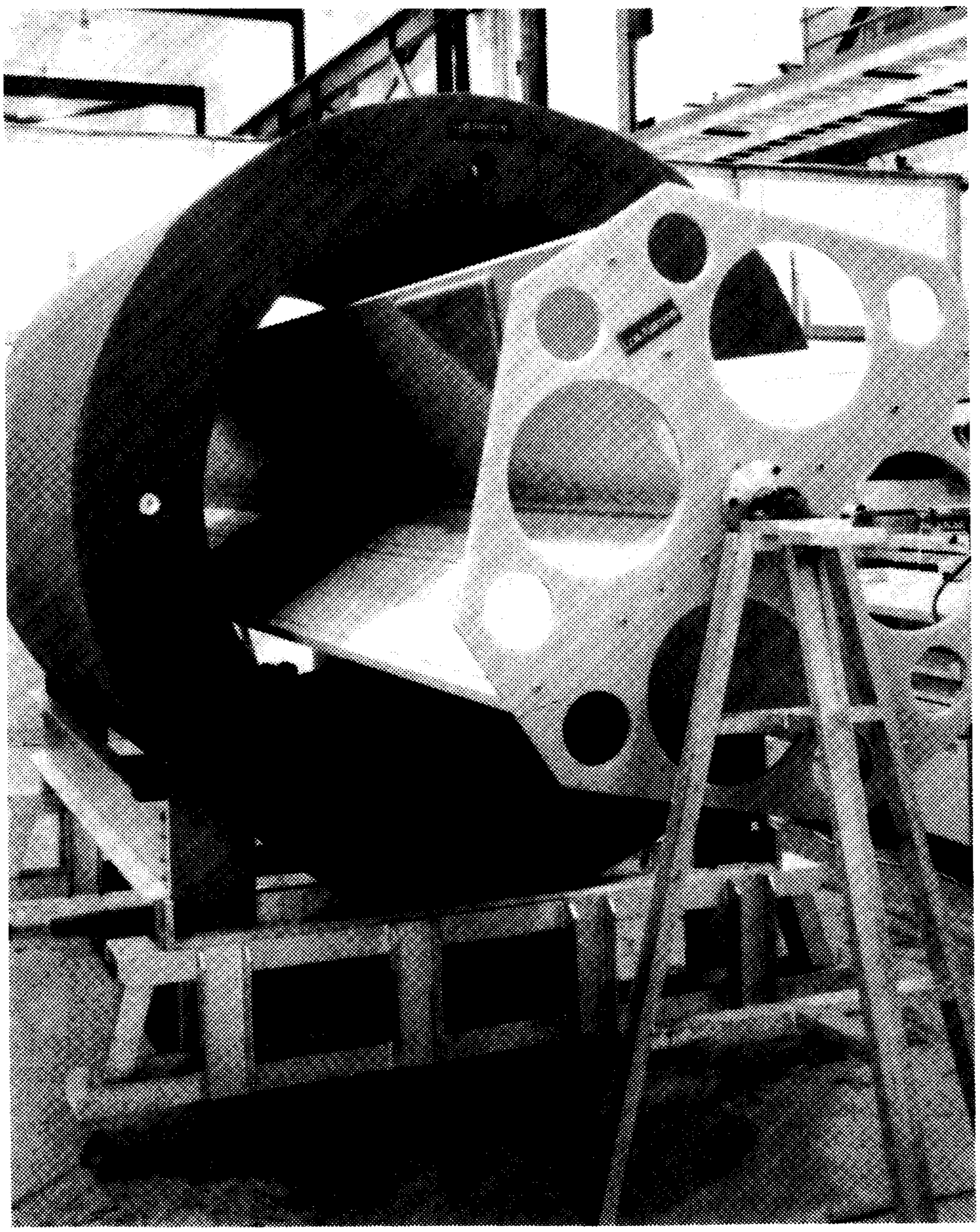

Fig. 7 Los Alamos 1.25 m bore quadrupole and measuring coil

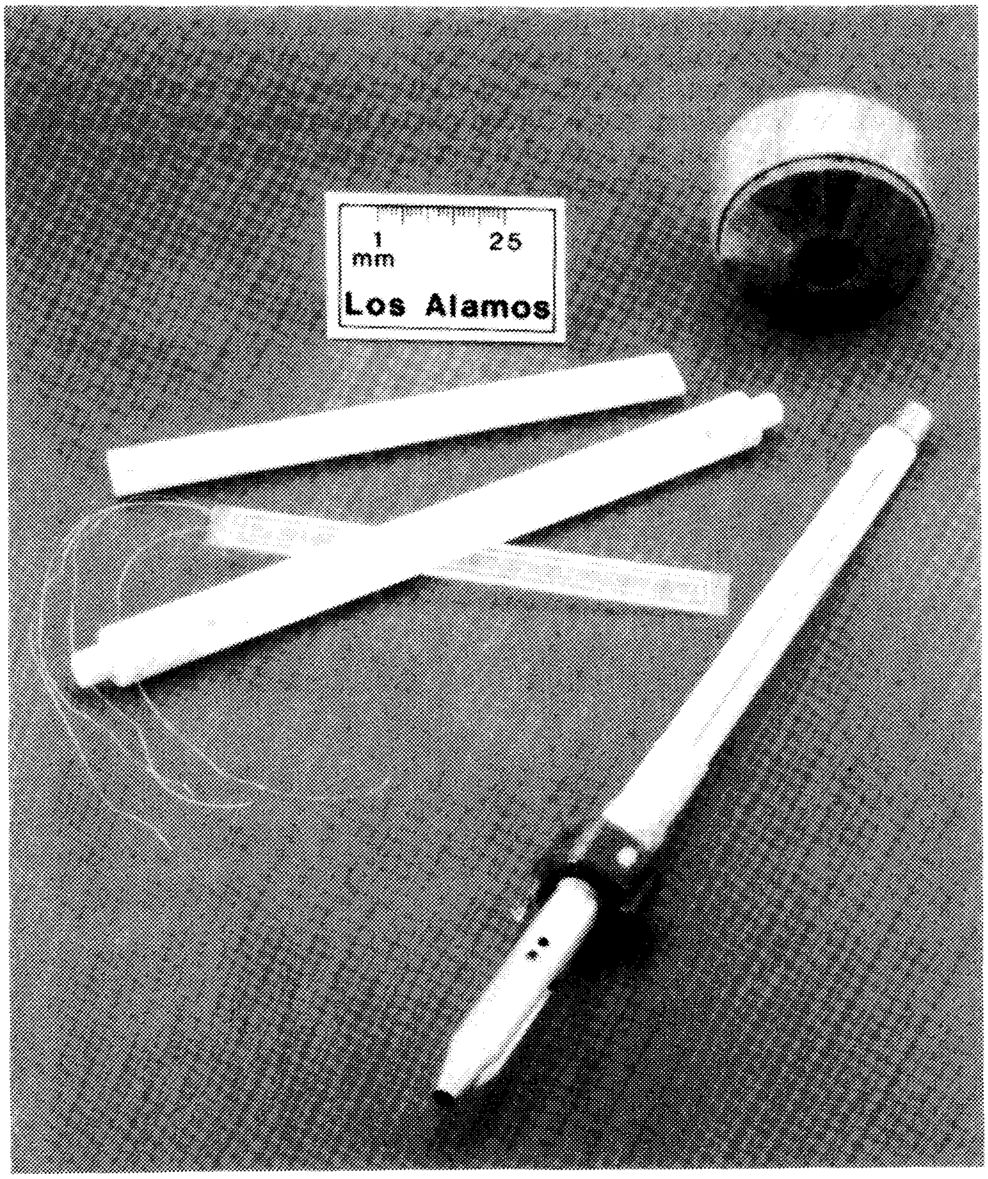

Fig. 8 Los Alamos 10 mm bore quadrupole and measuring coil

3.3 Superconducting dipoles and quadrupoles

Measuring devices have been developed for the superconducting magnets for Fermilab's TEVATRON [3] and DESY's HERA [4]. Work is in progress on measurement schemes for the Superconducting Super Collider (SSC) in Texas. One of the most developed devices is the Mole, built at Brookhaven National Laboratory (BNL) on Long Island, New York, for both the SSC and the Relativistic Heavy Ion Collider (RHIC) [5]. Much ingenuity has gone into the choice of components that will operate in high magnetic fields, such as gas-driven motors (n), piezo-electric motors (p) and iron-free electric motors (o). However, the gravity-sensor, needed to give a reference direction for field orientation measurements, is an electrolytic device (j), and so it requires a near-room-temperature environment for its operation.

4. HIGH-PRECISION FIELD POSITION REFERENCES

Next-generation colliders will have beam sizes at their interaction points 1 μm wide by 60 nm high. The precision of determining the nodal-point of a quadrupole for such beams needs to be better than 30 μm, and the offset of an attached beam position monitor must be known to 5 μm in order to make active magnet positioning possible. A measurement bench has been constructed at SLAC, Stanford, California, USA [7] that uses the same stretched wire for both measurements. The wire is vibrated in the magnetic field for nodal-point determination, and carries 2 ns pulses at 1 kHz for finding the electrical center of the beam-position monitor. The resulting wire positions are read out by a high-resolution microscope (n), and are transferred to external positioning references by a coordinate measuring machine. The equipment layout is shown in Fig. 9.

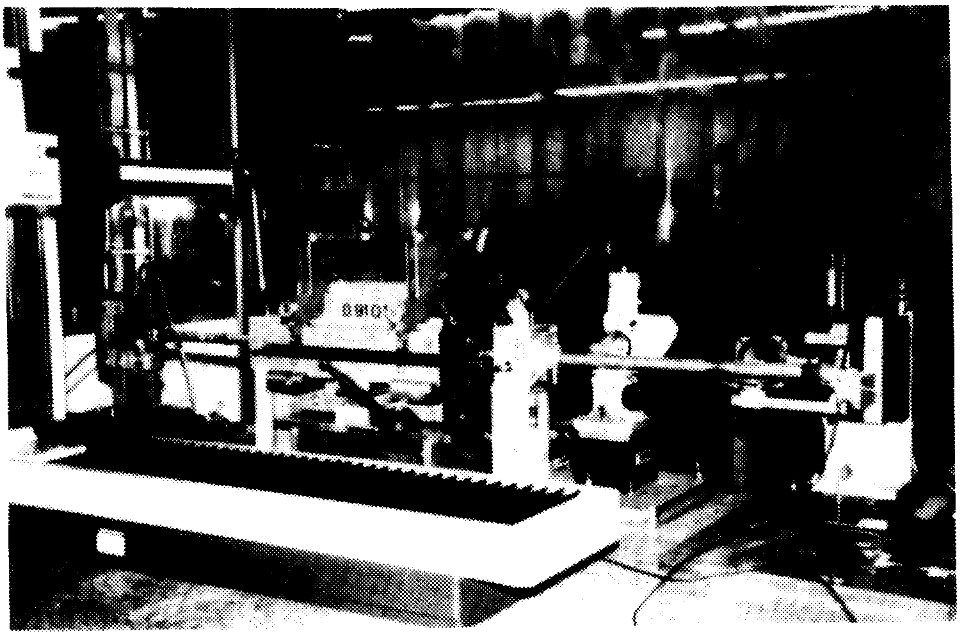

Fig. 9 SLAC stretched-wire equipment

5. SOURCES

Some representative sources are given here for the hardware described: it is not intended to be exhaustive. Note that some of the references also list sources [6], for example:

(a) Accelerometers, piezo-resistive	IC Sensors, 1701 McCarthy Blvd., Milpitas, CA 95035
(b) Accelerometers, piezo-resistive	Nova Sensor, 1055 Mission Court, Fremont, CA 94539
(c) Analyzer, spectrum	Hewlett-Packard (Model 3582A), 3000–T Hanover St., Palo Alto, CA 94304
(d) Ball screws	Saginaw Products Corp., 69 Williamson St., Saginaw, MI 48601
(e) Bearings, linear	Thompson Industries, Inc., Port Washington, NY 11050
(f) Coils, printed circuit	Microphase, 2820 Broadbent Parkway NE, Albuquerque, NM 87107
(g) Encoders, angular	BEI, 9223 Deering Ave., Chatsworth, CA 91311
(h) Hall probes	F.W. Bell (BHT-703), 6120–-T Hanging Moss Rd., Orlando, FL 32807

(i) Hall probes	Siemens AG, Hildes Hiemer Str. 7, D–3014, Hanover, Germany
(j) Level, electrolytic	Spectron Glass & Electronics, Inc., P.O. Box 13368, Hauppage, NY 11788
(k) Measuring machine, six-degree-of-freedom	ANASPEC Elektro–Optik GmbH, Wiesenstrasse 2, 6140 Bensheim 1, Germany
(l) Measuring stands, Multipole	Danfysik AS, Moellehaven 31, DK–4040 Jyllinge, Denmark
(m) Microscope, precision	Olympus (Japan) on a Micro–Controle (France) stage
(n) Motors, gas-driven	Zo–Air Co., 1320–6 Lincoln Ave., Holbrook, NY 117741
(o) Motors, iron-free	Micro–Mo Electronics Inc., 742 Second Ave., St. Petersburg, FL 33701
(p) Motors, piezo-electric	MicroPulse Systems, Inc., 3950 Carol Ave., Santa Barbara, CA 83110
(q) Motors, stepping	Slo–Syn, Superior Electric Co., Bristol, CN 06010-7488
(r) Resolvers, synchro	Computer Conversions Corp., 6 Dunton Court, E. Northport, NY 11731
(s) Stages, three-axis	Burleigh Instruments Inc., Burleigh Park, Fishers, NY 14453

6. ACKNOWLEDGMENTS

I am indebted to many people for the information in this paper. They include:

BNL, Long Island, NY USA, Peter Wanderer, George Ganetis

CERN, Geneva, Switzerland, Louis Walkiers

DANFYSIK, Jyllinge Denmark, Povl Abrahamson

G.S.I., Damstadt, Germany, Gebhart Moritz

LANL, Los Alamos, NM USA Robert Kraus, David Barlow

P.S.I., Villigen, Switzerland, Branko Berkes, Oliver Szavits

SLAC, Stanford, CA USA, Gerry Fischer, Robert Ruland

SSC, Dallas, TX USA, Zachary Wolf

TRIUMF, B.C. Canada, Paul Reeve, Alan Otter.

REFERENCES

[1] E. DeVita, D. Evans, P. A. Reeve, Automated Computer Controlled Magnetic Field Survey System, Design Note TRI-DN-84-70, TRIUMF, Vancouver, BC, Canada.

[2] O. Pagano, P. Rohmig, L. Walckiers and C. Wyss, A Highly Automated Measuring System for the LEP Magnetic Lenses, Journal de Physique, Colloque C1–1984 (MT-8), (1984) C1–949.

[3] B. C. Brown, W. E. Cooper, H. E. Fisk, D. A. Gross, R. Hanft, H. P. Kaczar, J. E. Pacnick, C. W. Schmidt, E. E. Schmidt and F. Turkot, Report on the Production Magnet Measurement System for the Fermilab Energy Saver Superconducting Dipoles and Quadrupoles, IEEE Trans. Nucl. Sci., NS–30, (1983) 3608.

[4] H. Brueck, R. Meinke, P. Schmuser, Methods for Magnetic Measurement of the Superconducting HERA Magnets, Kerntechnik 56 (1991) 248-256.

[5] G. Ganetis, J. Herrera, R. Hogue, J. Skaritka, P. Wanderer, E. Willen, Field Measuring Probe for SSC Magnets, IEEE Particle Accel. Conf., Washington DC, 1987, 3, pp. 1393-1395.

[6] G. E. Fischer, V. E. Bressler, J. K. Cobb, D. R. Jensen, R. E. Ruland, H. V. Walz, and S. H. Williams, Precision Fiducialization of Transport Components, SLAC–PUB–764 (1992).