MECHANICAL EQUIPMENT

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Abstract
Mechanical equipment is an integral part of each magnetic measurement. In this contribution the importance of mechanical tolerances is demonstrated with some examples and the principal rules in order to reduce the influence of mechanical errors are discussed. In the second part typical benches are presented for almost every measurement task. In the appendix a non-complete list of companies which produce or sell mechanical equipment is given.

1. INTRODUCTION
The successful operation of an accelerator requires:

- extremely tight magnetic field tolerances which have to be proved by measurements
- a proper alignment of the magnets

Thus we need mechanical equipment

- to check the mechanical tolerances of the magnets
- to make accurate magnetic measurements
- to set precise fiducial marks which are accessible after the installation of the magnets in the accelerator

In the field of magnetic measurements the mechanical equipment is mainly used for the positioning and moving of the sensor (coil, Hall probe etc.). Its specific design depends on the applications, i.e. on the field property we want to measure (transfer function, field boundary, field quality etc.), on the accuracy that is required, and on the shape and the symmetry of the magnetic field.

2. THE INFLUENCE OF MECHANICAL TOLERANCES ON THE ACCURACY OF MAGNETIC MEASUREMENTS
The accuracy required for magnetic measurements leads usually to very tight mechanical tolerances. I will demonstrate this with four examples.

2.1 Rotating harmonic coil
The influence of the mechanical errors on the results of magnetic measurements with a rotating harmonic coil is covered theoretically in several publications [1–3]. The main sources of measurement errors during coil operation are:

- error due to transversal displacement of the rotational axis
- error due to angular shifts

These effects depend on the angular position.
Transversal displacement is caused by the coil not rotating in a perfect circle due to sag and bow-effects and imperfect bearings. This error is not important for dipoles.

Angular shift means azimuthal vibrations induced by a lack of stiffness of the shaft and couplings or by the stepping motor. This effect influences the results for quadrupoles and dipoles as well.

These mechanical imperfections lead to errors in the measured harmonic coefficients. The relation is given in the following formulas

\[
\varepsilon b_n = \frac{n}{2} \sum_{k=1}^{\infty} \left( \delta_k (b_{|n+k|} + b_{n+k}) + \varepsilon_k (a_{|n+k|} - a_{n+k}) \right)
\]

\[
\varepsilon a_n = \frac{n}{2} \sum_{k=1}^{\infty} \left( -\delta_k (a_{|n+k|} + a_{n+k}) + \varepsilon_k (b_{|n+k|} - b_{n+k}) \right)
\]

for transversal displacement

\[
\text{Displ} = R_{\text{ref}} \cdot \sum_k \left( \delta_k \cdot \cos(k\theta) + \varepsilon_k \cdot \sin(k\theta) \right)
\]

and by

\[
\varepsilon b_n = \frac{n}{2} \sum_{k=1}^{\infty} \left( \delta_k (a_{|n+k|} + a_{n+k}) + \varepsilon_k (b_{|n+k|} - b_{n+k}) \right)
\]

\[
\varepsilon a_n = \frac{n}{2} \sum_{k=1}^{\infty} \left( -\delta_k (b_{n+k} + b_{|n+k|}) + \varepsilon_k (a_{n+k} - a_{|n+k|}) \right)
\]

For angular shifts [2].

\[
\theta_{\text{meas}} = \theta + \sum_k \left( \delta_k \cos k\theta + \varepsilon_k \sin k\theta \right)
\]

\(\delta, \varepsilon\) are the relative amplitudes of the distortion and \(b, a\) are the normal and skew field coefficients.

A field harmonic present in the magnet can introduce erroneous terms of higher and lower orders, and the error is basically given by the product of the amplitude of the harmonic coefficient and the error amplitude. Thus the main contribution is due to the main field component.

In order to reach a relative accuracy of the higher harmonic coefficients of the order of \(10^{-4}\) we need for example, at a typical radius of 40 mm, a stability of the axis of some \(\mu m\) and a precision of the angular measurement better than 0.1 mrad.

It is almost hopeless to fulfill these conditions.

2.2 Mapping of the Electron Cooler solenoid

In an Electron Cooling device the warm ion beam is cooled down by a cold electron beam. By elastic Coulomb collisions between electrons and ions travelling together through the field of the cooler solenoid the velocity distribution of the ion beam is reduced, the beam gets colder. Good cooling efficiency requires a very high field homogeneity of this solenoidal field. Especially critical are the transverse field components, because these limit the reduction of the transverse velocity. It is almost impossible to build a solenoid with transverse components smaller than 0.1% of the main longitudinal component. Thus, so-called correction windings are usually installed in order to compensate for the transverse components.
The solenoid is 2–3 m long and the variation of the transverse components relative to the main component should be less than 0.01%. We at GSI used a 3D probe head with three Hall probes (Fig. 1). The very critical mechanical requirement is that the orientation of the probe head in front of a 4-m long cantilevered beam must be stable within about 0.01 mrad. Otherwise the main component would lead to a wrong measurement of the transverse component. That demands very high accuracy and stability of the stage that is used. Using the mirror in front of the probe head we check this regularly by autocollimation, i.e. by measuring the angle between the incident and reflected light.

Fig. 13D probe head with three orthogonal Hall probes

2.3 Mapping of an Insertion Device

The field of an Insertion Device (ID) (wiggler or undulator) should not disturb the closed orbit of a stored beam, that means that an electron should neither be deflected nor transversely displaced. This leads to the requirements that the first and second field integral have to be zero, i.e.

\[ \int B(s) \, ds = 0 \quad \text{and} \quad \int \int B(s,y) \, ds \, dy \, dy = 0 \]

Thus these field integrals have to be measured. The measurement errors typically have to be less than 100 G•cm and 100 G•cm² respectively.

One method that measures both the local and the integral fields is the mapping of the ID point by point in the longitudinal direction. The integral field is numerically calculated by summation over the point measurements:

\[ \int B \cdot dz = \sum B_i \cdot \Delta z_i \]

The integral reproducibility error is given by

\[ \Delta \int B \cdot dz = \Delta B^{rms} \cdot \Delta z \cdot \sqrt{N} \]

where \( N \) is the number of points, \( \Delta z \) the step width and \( \Delta B^{rms} \) the rms error of every point measurement.

Let us consider only the field error due to erroneous positioning:
I use as an example the Advanced Light Source (ALS) Insertion Device [4, 5]: It is 5.5 m long, $\Delta z = \pm 0.22 \text{ cm}$, $N = \pm 2500$, maximum field 0.9 T, wavelength $\lambda = \pm 5.0 \text{ cm}$. The field oscillates rapidly with the wavelength $\lambda$ between -0.9 T and +0.9 T.

The error of the local field measurement due to a position uncertainty $\delta z$ is given by the formula:

$$dB = B_0 \frac{2\pi}{\lambda} \sin(2\pi \cdot \frac{z}{\lambda}) \cdot \delta z$$

and

$$\Delta B^{rms} = B_0 \frac{2\pi}{\sqrt{2}} \frac{\delta z}{\lambda}$$

With the position reproducibility $\delta z$ of $1 \mu \text{m}$ we get $\Delta B^{rms} = \pm 0.8 \text{ G}$ and the contribution to the integral error by the position accuracy only is $10 \text{ G cm}$.

### 2.4 Measurement of the integral field strength $\int Bd l$ with the stretched wire method

When a stretched wire is moved transversely through a magnetic field by a distance $dx$, the flux through the wire loop changes and a voltage $V$ is induced that can be integrated:

$$\int Bd l \approx \frac{1}{dx} * \int V dt$$

One sees immediately that the relative error of the position has to be of the same order as the desired accuracy of the integral field. A relative integral field accuracy of $10^{-4}$ and a step width of 10 mm requires a precision of the position measurement of $1 \mu \text{m}$.

### 3. STRATEGIES FOR REDUCING THE INFLUENCE OF MECHANICAL ERRORS

#### 3.1 Use the best and most suitable equipment you can get

For example:

- good spring-loaded bearings for the minimisation of transverse vibrations
- good encoders
- interferometer for position measurement
- DC motors instead of stepping motors to reduce torsional vibrations

Do the components also operate properly in a high field and low temperature environment?

#### 3.2 Use the appropriate material

- no magnetic material
- no conducting material
- high torsional stiffness (for example for the shaft and coupling of the rotating coil, $100 \pm \text{Nm/mrad}$)
- high bending stiffness for a long cantilevered beam (good modulus/weight ratio)
3.3 Measure the correct sensor position

The position or orientation of the sensor (Hall probe/coil etc.) should be measured as close to the sensor as possible. That means for example:

- place the encoder near the rotating coils
- place the mirror for autocollimation measurements close to the Hall probe head
- place the interferometer reflector correctly for accurate position determination

3.4 Use intelligent design

The components may not be available on the market or are too expensive, the tolerances in machining are too tight.

- bucking coils compensate the main harmonic and thus reduce the influence of lateral and torsional vibrations on the measurement results
- damp the vibrations of the motor/gear by flexible coupling
- vertical orientation of the rotating coil/stretched wire avoids the influence of sag
- double search coils for gradient measurement are independent of the position accuracy

3.5 Use another method

A general strategy should be to double check the results by several methods!

- instead of mapping: stretched-wire method
- instead of stretched wire: flip- or search-coil method
- instead of mapping the three components of the field, measure the orientation of the field by a compass needle [6] (Fig. 2)
3.6 Measure the errors

If you cannot get the required precision of your equipment, then you have to measure the errors and correct for:

- systematic errors which can be measured off-line and corrected for later using calibration tables
- random errors which can be measured on-line

For example: Calibration of the 3D Mapper stage versus on-line measurement by autocollimation and/or interferometer.

3.7 Average the results

By appropriate averaging over different orientations mechanical errors will cancel out:

- offset of the inclinometer
- misalignment of a Hall probe can be checked by a rotation of 180°
- coil orientation (relative to gravity) can be found by end-to-end inversion of the coil

4. SPECIAL EQUIPMENT VERSUS UNIVERSAL EQUIPMENT

This is an often discussed question. Should we build for each measurement task an individual test stand for every magnet or should we have just one test stand, that can be used for each measurement task and for all magnets in the laboratory? Obviously both ways do not work.

The advantages of special equipment versus universal equipment are given in the following table:

<table>
<thead>
<tr>
<th>Special equipment</th>
<th>Universal equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well suited since it</td>
<td>Available in the laboratory or on the market thus saving</td>
</tr>
<tr>
<td>• saves measuring time</td>
<td>• money</td>
</tr>
<tr>
<td>• improves accuracy</td>
<td>• time</td>
</tr>
<tr>
<td>allows†better†comparison</td>
<td>• man power for design and construction</td>
</tr>
<tr>
<td>(reference magnet)</td>
<td></td>
</tr>
</tbody>
</table>

Obviously we will build a well-suited specialised test stand for large series of magnets as well as for special magnets and magnets of extreme size.

In general each laboratory has some universal equipment. Whether you build a special test stand for a single magnet or not depends on your man power and the possible special demands the customer has.

5. MECHANICAL COMPONENTS
In Appendix 1 you will find a (incomplete) list of the most important mechanical components.

In the next two sections I will show you examples of mechanical equipment that have been built in the laboratories depending on the task that had to be done, i.e. on the properties of the magnet that had to be measured.

6. **BENCHES FOR THE MEASUREMENT OF THE MECHANICAL PROPERTIES OF MAGNETS**

During the production of normal-conducting magnets (especially in éstrangel magnets such as the LEP dipoles which are filled with concrete, and in laminated magnets) mechanical errors of the iron core are unavoidable. Thus one has to measure the

- gap height
- median plane position

as a function of the axial co-ordinate.

From these data one can find the average gap height, a possible gradient and the twist. One can then align the magnet correctly by bringing it up to the average mid-plane position and by removing the average roll and pitch.

I give two examples: One for the LEP dipoles [7] and one for the SLAC B-Factory High Energy Ring (HER) dipoles, both are C-type magnets.

The LEP bench is shown in Fig. 3. A carriage moves along the axial co-ordinate by rolling on the lower pole face of the gap and being pulled by a belt driven by a stepping motor. Five proximity detectors measure the position of the carriage in the gap and thus the gap height and the median plane. One four-quadrant photocell measures the position of the carriage relative to a laser beam and an inclinometer compares the tilt of the gap with the tilt of the reference surface on top of the core.

The bench used at SLAC is quite similar, but the proximity detectors are attached to an arm that is moved in the axial direction by a linear stepping motor. An inclinometer controls the orientation of the arm during the movement. A ëgarageï (an idealised gap) serves as a reference for mid-plane and gap height.

Fig. 3 Bench for measurement of the

Fig. 4 DESY HERA stretched-wire system
7. **BENCHES FOR THE MEASUREMENT OF THE MAGNETIC PROPERTIES OF MAGNETS**

7.1 **Standard accelerator magnets**

7.1.1 **Integral field strength**

We know several methods to measure the integral field strength directly, i.e. not by mapping the field point by point and then integrating the field numerically.

**Stretched-wire method**

Figure 4 shows schematically the bench at DESY for the HERA measurements [8]. A wire (usually tungsten or CuBe) is stretched between two points, fixed at one end and held by a tension spring at the other. The return wire closes the flux loop outside the yoke of the magnet. The wire can be moved by two high-precision x-y stages (resolution: 1µm), which operate in the master-slave mode. The induced voltage is integrated. The relative accuracy of the step width must be of the same order as that of the $B_{1d}$. Thus the position is often measured by an interferometer. Figure 5 shows the Sincrotrone Trieste bench while measuring an Insertion Device [9]. The x-y stages are mounted on a common 3.2-m long granite base plate. Similar benches can be found at SLAC, ESRF, the former SSC [10], CEBAF [11] and FERMILAB [12].
For the CTF (CLIC Test Facility) (Fig. 6) at CERN, a stretched-wire bench for quadrupoles of apertures as low as 10 mm has been developed [13]. In this case the magnet is moved, not the wire. The bench is vertical. The positions are controlled by new precise x-y capacitive sensors developed at CERN.

The stretched-wire bench can be used also for a *flip-coil* measurement. In this case the necessary positional accuracy of the stages is reduced. A rotation stage added to the x-y stages and driven by a step or servo motor flips the search coil. The principle is shown in Fig. 7.

If the stages are mounted on two separate base plates, you can omit one stage and replace the coil by a point probe at the end of a long probe arm so creating a very universal measuring device. Sincrotrone Trieste are presently changing the design of their bench in this way.

These methods work well, as long as the magnet is basically straight or at least the sagitta small compared to the aperture. For curved magnets flipping is not possible, so the *curved search coil* moves azimuthally out of the magnet, either on rollers or air cushions. Two possible schemes are shown in Fig. 8. At the top is the solution adopted at GSI for the SIS dipoles [14], the other solution was proposed for the ESRF dipoles. In both cases emphasis is put on the necessity to make a null measurement relative to a reference magnet. A different method was adopted at ANL for the curved C-type dipole magnets of the Advanced Photon Source (APS) [15]. A search coil is mounted on a flat board and moved in radial and vertical direction by several precision stages mounted on a common 4-m long base plate (accuracy: 0.01†mm) (Fig. 9).
7.1.2 Field harmonics

*CERN LEP quadrupoles rotating coil*

The prototype of a standard bench for the rotating coil was developed at CERN by Louis Walckiers and co-workers for the LEP quadrupoles [16]. This type was later built by Danfysik and sold to different laboratories (ESRF, ANL, etc.). It is used to determine the field harmonics, the field axis and the field direction. A schematic side view is shown in Fig.10.

![Diagram of CERN LEP quadrupoles rotating coil](image)

**Fig. 10** CERN LEP quadrupoles rotating coil

The coil system consists of:

- radial coil and bucking coil (coil radius typically 100 mm)
- end coils/central field coil
- air bearings (lateral displacement less than 0.01\(\uparrow\)mm)
- DC motor
- absolute angular encoder (triggers the integrator)
The automatic magnet positioning and aligning system consists of:

- motors for vertical/horizontal translation and rotation around three axes. Air cushions are used for the horizontal translation.
- laser, position-sensitive light detector and electronic inclinometers (resolution: 0.01 mrad) for pre-alignment and for setting the fiducial marks

Overall specifications:

- relative accuracy of integrated main harmonic: $\pm 3 \times 10^{-4}$
- accuracy of a multipole component relative to the main component: $\pm 3 \times 10^{-4}$
- angular phase absolute accuracy: $\pm 0.2$ mrad
- lateral positioning accuracy of magnetic centre with respect to the rotation axis: $\pm 0.03$ mm
- positioning accuracy of alignment targets with respect to coil axis: $\pm 0.03$ mm

The photograph of the bench shown in Fig. 11 was taken at ANL.

**Coil train for the CERN LHC dipoles**

For the measurement of the high magnetic field of the 15-m LHC dipoles two, long induction coil trains (12 coils connected mechanically together, rotating in ceramic pipes with an outer diameter 36 mm) are rotated from the outside of the magnets through shafts by a Twin Rotating Unit (TRU). From the specification of this TRU, I took the following scheme, that shows the principle layout with all the necessary components (Fig. 12).
Main rotating parts:

1) Signal cable from CERN measuring coil
2) Flange connection to the shaft of the rotating coil train
3) Rotating support for axle (high quality ball bearings)
4) Flexible cable connection (three turns in both directions, flat-ribbon cable (50 twisted pairs))
5) Reference surface of axle (adjustable, to measure the orientation of the axle relative to gravity): ±0.05 mrad
6) High precision, hollow, shaft-angle encoder: accuracy ±0.05 mrad
7) Adjustable level meter on the top: measuring range: ±15 mrad, accuracy: ±0.05 mrad
8) Torque meter supervises the friction during rotation: max. 0.2 Nm
9) Flexible coupling for smooth rotation of the shaft and minimisation of vibrations
10) Overload clutch for protection (can open if torque > 0.1†N m)
11) End switches and limiter of rotation
12) Drive unit (servo motor/reducer)

The torsion stiffness upstream of the encoder (in the coil direction) is specified as >100 Nm/mrad.

**Mole for the low-field measurement of the CERN LHC magnets**

Much work has been invested at BNL, SSC [17, 18] and at CERN [19] in the development of a rotating-coil device that can be moved through the small bore of a long superconducting magnet, the so-called émolef. Let me present here the low-field mole (±500†Gauss) for LHC dipole measurements. Figures 13 and 14 are taken from the specification.
The mole (OD 46†mm) is pulled through the magnet by pulleys over two reels at either side of the magnet. The lateral position is determined by a PSD that monitors the laser beam. Internally it consists basically of the following components (all sealed in a stainless steel cylinder):

- level meter (limited range, accuracy: 0.05 mrad) and level motor
- coil motor (must not create an outside field >0.02 G)
- encoder (reproducibility of each trigger < 0.05 mrad, zero within ± 0.05 mrad)
- rotating harmonic coil (700 mm long)
- rotating PSD
- reference surfaces on the mole in order to check the zero of the PSD, level meter, and encoder

Figure 15 shows how the prototype mole looks in real life. Here the coil is driven by a long shaft, no motor is used. You see (from right to the left) the gravity sensors, the air brake, the ball roller, the encoder, the slip rings and the coil itself. Some moles are also equipped with Hall or NMR probes. Components for high-field moles have also been tested at CERN.

![Fig. 13 CERN LHC low-field mole (overview)](https://example.com/fig13)

![Fig. 14 CERN LHC low-field mole (details)](https://example.com/fig14)
Rotating coils of extreme size

You can find both examples at LANL, one quadrupole with a bore as large as 1.25 m and as small as 10 mm. The corresponding coils are built on a large G-10 frame; For the small one a printed-circuit technique was used. They are presented in the proceedings of the CAS  "Magnetic measurement and alignment" course 1992 in Montreux [20].

7.1.3 Field Mapping

Field maps are often required for:

- ray tracing
- the calculation of fringe field properties
- the determination of field overlap effects
- the calculation of special integrals (for example: $\int B \cdot ds \cdot \delta ds$)
- the construction of correction windings

One can design either special equipment, usually a little carriage carrying a field sensor that moves along a given curve (mostly the bending radius of the curved dipole magnet) or use co-ordinate measuring machines (CMM) with several degrees of freedom. The sensors measure either the main component or all field components. Some benches use several probes calibrated and oriented ëin situí.

Examples:

Standard CMM bench

Figure 16 shows a typical CMM bench with three orthogonal axes. All three tables run on linear ball bearings and are driven by stepping or servo motors via lead screws. This stage was used to map the fringe field region of the dipoles of the APS at ANL [21]. A similar bench exists at TRIUMF. With an additional auxiliary table, operated in the slave mode, they operate the bench as a flip-coil bench.
The Luge operated at the ALS in Berkeley

The Luge was constructed as a high speed mapping device for the measurements of the Insertion Devices of the ALS [4, 5]. A custom-built stage moves axially through the gap of the 5-m long ID. It is supported on one side by a rail and on the other side by a pneumatic cylinder that provides the mechanism for axial translation (Fig. 17). The horizontal and vertical positions can be varied. The field components are measured by a Hall probe and point coils. As we have seen earlier in the error discussion, the accuracy of the axial position must be $1 \mu$m. Thus it was measured by a laser interferometer. The 6-m scan takes less than one minute.

The GSI Mapping device

This device has six degrees of freedom, three translations and three rotations [22]. The probe head is mounted at the end of a long probe arm. In order to minimise oscillations of this arm, it was necessary to minimise any friction, so only air cushions and air-bearing slide shoes are used.
The complete system is shown in Figure 18. The three-dimensional measuring machine itself consists of a large granite table on a support sub-frame, 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 linear scan ranges are 2700 mm in the axial (x) and 1000 mm in the transverse (z) and vertical (y) direction. Resolution is 1 µm and 20 µrad. The rotation range around the x-axis is 360°, ± 100° around the y-axis and + 30° around the z-axis. The maximum speed is 27 mm/s. The whole machine can be moved either by a crane or air cushions.

Fig. 18 The GSI mapping device

The probe arm consists of three long, carbon-fibre, epoxy cylinders that fit into each other and are bonded together to a maximum length of 4 m. Three Hall probes are mounted orthogonally to each other in a temperature-stabilised probe head. The orientation of the probes can be determined relative to the mirror in front by auto-collimation. The internal direction cosines of the probe are measured with a precision of 1 part in 10000.

The system was tested in three ways:

- Mechanically by electronic level meters: The maximum deviation of the flatness of the table was 8 µm, the slideways were straight within 4 µm. The three axes are orthogonal within 0.01 mrad.
- Optically by auto-collimation using two mirrors, one attached to the vertical slideway and the other in front of the probe: Moving with a speed of 20 mm/s along the x-axis, the maximum angular deviations were 0.01 and 0.08 mrad, respectively—the latter value includes the effect of the vibrations of the long probe arm.
• By magnetic measurements in a quadrupole: By averaging over 100 ms the results were improved by a factor of 4.

CERN PS magnet mapping bench

The combined-function magnet of the PS (dipole, quadrupole and sextupole!) is mapped in the following way [23] (Fig. 19): A trolley is driven pneumatically on 6-m long titanium rails along the longitudinal axis in steps of 20 mm defined by precise notches. The trolley carries a set of 15 Hall probes, aligned perpendicularly to the longitudinal axis. The lateral displacement is $\pm 10$ mm. It is used to calculate the gradient. Each time the trolley has moved axially the absolute lateral position is checked and corrected by a laser/PSD system to an accuracy of 0.01 mm.

![CERN PS magnet mapping bench](image)

Fig. 19 CERN PS magnet mapping bench

Measuring benches at LNS

At the LNS (Laboratoire Nationale de Saturne) at Saclay, large benches with modular rails (curved and linear) up to 6-m long were developed. A carriage that is moved pneumatically along these rails can carry up to 100 Hall probes on a transverse 2-m long arm. Thus an area of 12 m$^2$ can be measured in a short time. A special hall probe calibration bench allows 16 encased probes to be calibrated automatically in a reference magnet within 3 hours.

7.1.4 Field direction

The field direction is usually found by mechanical measurements (only for conventional magnets) as described above or by the rotating-coil or stretched-wire method already described.

7.1.5 Field axis
This is covered in the talk "Finding the axis" by P. Sievers in these proceedings [24].

7.1.6 Material

Permeameter/Coercimeter

This topic is covered in the contribution of J. Billan to these proceedings [25].

Permanent magnet block measurement (LBL)

For the ALS Insertion Devices the magnetic moment of blocks of permanent magnets had to be measured [26]. The following objectives for a Helmholtz coil system were established:

- measure the three components of magnetic momentum to an accuracy of ±0.1 %
- fast processing: 20 blocks per hour, more than 10000 altogether
- easy to use for an unskilled operator

This led to the decision to build an automated system. It is shown schematically in Fig. 20. The block holder in the centre of the Helmholtz coils attached to a long shaft is rotated 360° by a servomotor. The angle is measured by an encoder. A Fourier analysis of the voltage induced in the coils gives two components of the magnetic momentum. Then the block holder is flipped by 90° and rotated again by 360°. This measurement delivers the third momentum component.

![Image of Permanant magnet block measurement (ALS Berkeley)](image_url)

Fig. 20 Permanent-magnet block measurement (ALS Berkeley)

7.2 Special magnets

7.2.1 Cyclotron magnet mapping
At PSI, Switzerland, and NAC, South Africa special benches for the mapping of cyclotrons have been built. These are described in the proceedings of the CAS ëMagnetic measurement and alignmentí course 1992 in Montreux [20].

7.2.2 Detector solenoids

Again this topic is covered in the proceedings of the CAS school in Montreux [27] and in the contribution ëDetector magnet measurementí of D. Newton to these proceedings [28].

7.2.3 Electron cooling device (including toroids)

The storage rings LEAR at CERN [29] and ESR at GSI were fitted with electron cooling devices. This required mapping of the whole device including the toroids, gun and collector solenoids. The solution was to bring the whole device into the horizontal plane. Then the whole field path was split in boxes that were measured from various directions (Fig. 21). The field components inside the boxes can be evaluated from measurements on the boundaries only [30].

![Fig. 21 Measuring boxes of the GSI ESR electron cooler.](image)

ACKNOWLEDGEMENTS

I thank all my colleagues in the laboratories in Europe and the US for helpful discussions and generously providing information and material.

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REFERENCES


[28] D. Newton, "Detector magnet measurement", these proceedings.


### APPENDIX 1

#### Mechanical/Optical Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Specifications/Features</th>
<th>Companies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear-, Rotation Table/Stages/ Optical Components</td>
<td>For example: Micro controle MT160</td>
<td>Micro Controle/Newport, France Klinger Scientific Corp., U.S.A. Spindler &amp; Hoyer, Germany Burleigh Instruments Inc., U.S.A. SKF, Germany</td>
</tr>
<tr>
<td>Linear encoder</td>
<td>Temp. coeff.: 0/°K (substrate: glass ceramics) to 10 ppm/°K (glass)</td>
<td>Heidenhain, Germany</td>
</tr>
<tr>
<td>Rotary encoder (incremental)</td>
<td>Line counts up to 10000/revolution Interpolation by factor 4 and 5 Accuracy: 0.05 mrad</td>
<td>Heidenhain, Germany Gurley Precision Instruments, U.S.A. BEI, Encoder System Division, U.S.A. Litton Precision Products, Germany Baumer Electric AG, Switzerland CODECHAMP, France</td>
</tr>
<tr>
<td>Interferometer</td>
<td>Resolution: up to 1nm U.S.A.</td>
<td>Hewlett-Packard, U.S.A. Zygo Corp., U.S.A. Teletrac Inc., U.S.A. Spindler &amp; Hoyer, Germany</td>
</tr>
<tr>
<td>Capacitive sensor</td>
<td>Position accuracy (x-y): 1µm</td>
<td>FOGALE nanotech, France Capacitec, U.S.A.</td>
</tr>
<tr>
<td>Air-motor</td>
<td></td>
<td>Zo-Air Co., U.S.A. Physik Instrument, PI Ceramic GmbH, Germany Shinsei, Japan</td>
</tr>
<tr>
<td>Piezo-Electric motor</td>
<td></td>
<td>MicroPulse Systems, Inc, U.S.A.</td>
</tr>
<tr>
<td>Step, microstep motor</td>
<td>Microstep: up to 50000 steps/rev.</td>
<td>Parker Hannifin Corporation, Compumotor Division, U.S.A. Micro Controle/Newport, France Berger GmbH, Germany FENWICK, France</td>
</tr>
<tr>
<td>Servo-motor</td>
<td></td>
<td>Micro Controle/Newport, France Maxon motor Interelectric, Switzerland Maxon Precision Motors, Inc, U.S.A. Minimotor SA, Switzerland Portescap, Switzerland Portescap U.S., Inc., U.S.A.</td>
</tr>
<tr>
<td>Component</td>
<td>Specifications/Features</td>
<td>Companies</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------------------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Ball bearings (steel)</td>
<td>Centre-position stability: 1–2µm</td>
<td>FAG, Germany</td>
</tr>
<tr>
<td>Ball bearings (ceramic glass)</td>
<td>Centre-position stability: some µm</td>
<td>Wemh’ner&amp;Popp, Germany</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Koba Electronics, Japan</td>
</tr>
<tr>
<td>Slip rings</td>
<td></td>
<td>Schleifring, Germany</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Litton Precision Products, Germany</td>
</tr>
<tr>
<td>Inclinometer</td>
<td>Principle: capacitive position measure-ment of a pendulum</td>
<td>Wyler, Switzerland</td>
</tr>
<tr>
<td></td>
<td>Accuracy: 0.04 mrad</td>
<td>Schaevitz, c/o Althen Messtechnik, Germany</td>
</tr>
<tr>
<td></td>
<td>Resolution: 0.002 mrad</td>
<td></td>
</tr>
<tr>
<td>Gravity sensor /Tilt sensor</td>
<td>Principle: resistance measurement of an electrolytic liquid in a vial</td>
<td>Spectron / G+G Technics AG, Switzerland</td>
</tr>
<tr>
<td></td>
<td>Range: ± 1•, nearly-zero method</td>
<td></td>
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<tr>
<td></td>
<td>Resolution: 1 µrad</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temp. coefficient &lt;2µrad/•C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temp. compensated</td>
<td></td>
</tr>
<tr>
<td>Laser for alignment</td>
<td>For mounting in a spindle</td>
<td>Hamar Laser Instruments, U.S.A.</td>
</tr>
<tr>
<td></td>
<td>0.01 mm beam centre position</td>
<td>OPTILAS, France</td>
</tr>
<tr>
<td></td>
<td>0.002mm/hr/•C centering stability.</td>
<td>Gerhard Franck Optronic, Germany</td>
</tr>
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<tr>
<td>Position sensitive detector/diode</td>
<td></td>
<td>United Detector Technology, U.S.A.</td>
</tr>
<tr>
<td>Four-axis target</td>
<td>Two-axis centering: 0.01 mm</td>
<td>Hamar Laser Instruments</td>
</tr>
<tr>
<td></td>
<td>Squareness (pitch/yaw): 0.04mm/m</td>
<td></td>
</tr>
<tr>
<td>Auto-collimator</td>
<td>Resolution: 0.1µrad</td>
<td>Micro Controle/Newport, France</td>
</tr>
<tr>
<td></td>
<td>Range: ± 2mrad</td>
<td>Rank Taylor-Hobson, UK</td>
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<tr>
<td></td>
<td></td>
<td>Spindler &amp; Hoyer, Germany</td>
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<tr>
<td>Torquemeter /strain gauge</td>
<td></td>
<td>Kistler, Switzerland</td>
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<tr>
<td></td>
<td></td>
<td>Applied Geomechanics Inc., U.S.A.</td>
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</tbody>
</table>