# High Accuracy Field Mappings with a Laser Monitored Travelling Mole

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*Abstract*

The LEP spectrometer is an alternative method adopted to predict the LEP beam Energy. A bending magnet is flanked on either side by three beam position monitors (BPM) used to determine the deflection angle of the beam. In order to reach the desired accuracy on the beam energy a relative precision of a few $10^{-5}$ on the magnetic field integral is necessary. The magnet is a full-iron core dipole, 5.75 m long, of the MBI type used in the LEP injection region. It has been specially designed in order to have high field uniformity.

## 1 INTRODUCTION

During the the LEP spectrometer operation the change in the bending angle $\theta$ is detected by mean of the beam position monitors (BPMs) and the total integral B-field seen by the particles while travelling inside the spectrometer magnet (see Fig. 1) is evaluated. The beam energy is then calculated, being

$$\Delta\theta \propto \frac{\int_L Bdl}{E_{beam}} \qquad (1)$$

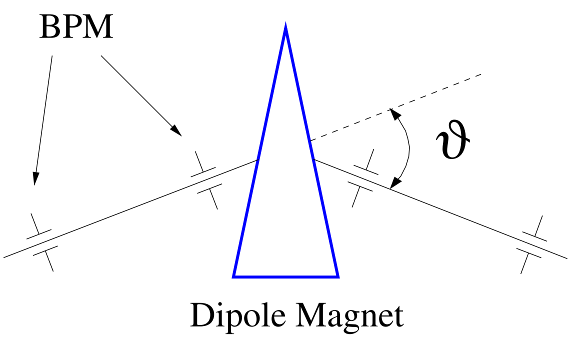


Figure 1: LEP Spectrometer schematic layout

## 2 MEASUREMENT REQUIREMENTS

The LEP beam energy calibration goal is to keep the relative error smaller than $1 \cdot 10^{-4}$. Considering the beam position measurements and the total integral field evaluation linearly independent, the single errors add quadratically. This leads to the requirement of a relative error in the field mappings not larger than $3 \cdot 10^{-5}$.
The total integral field seen by the particles along the magnet is evaluated during the LEP operation by reading the field in four fixed locations. The aim of the mapping was the estimation of the total integral by sampling

$$\frac{\Delta \int Bdl}{\int Bdl} = f(B_{ref}) \qquad (2)$$

and outline its possible changes due to environmental conditions. For this reason a first series of maps have been carried out in the laboratory by mean of a movable carbon arm equipped with magnetic field monitors [1], scanning different temperature levels and magnet conditioning.
The "mole" measurements were performed as a cross check and above all to investigate possible changes due to the magnet transportation in the LEP tunnel and the final spectrometer alignment and setup.
The mapping has the aim of estimating the total integral by sampling the local B-field and approximating the integral with a sum:

$$\int_{s_1}^{s_2} B(s)ds \approx \sum_{i=1}^{N} B_i \cdot \delta s_i \qquad (3)$$

## 3 MEASUREMENT SETUP OVERVIEW

The system has been developed to be accurate in the *length* and *field* measurement as well as transportable (laboratory-LEP tunnel) without compromising the reproducibility.

### 3.1 Mapping Mole

The mapping has been carried out with a mole travelling inside the vacuum chamber. A schematic diagram is shown in Fig. 2. The device has been designed in order to fulfill the requirements on the measurement accuracy. Fully non-magnetic materials have been chosen and basic static-dynamic calculations were executed to guarantee the necessary mechanical stability against stretching and torsion. Four bronze-beryllium springs are inserted in each of the

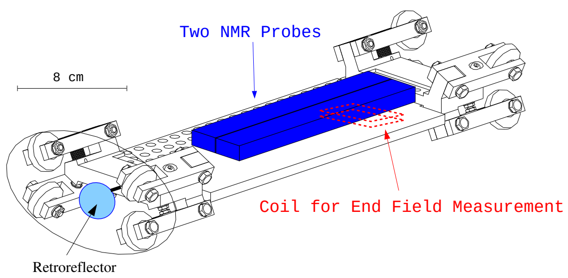


Figure 2: Schematic diagram of the mole.

upper wheels supports, in order to keep them stably pushed against the vacuum pipe walls. The vacuum chamber in the spectrometer magnet is lifted up by 2 mm from the center of the dipole yoke, in order to guarantee enough space between the lower pole tip and the beam pipe for the four fixed NMR probes. The alignment was carefully studied and the geometry was designed to put the NMR probes and the search coil in the center of the dipole gap, making them slide along the ideal beam trajectory.
The chariot is pulled by a toothed belt driven by a stepping motor. The belt has been chosen to have good elastic properties and stable behavior in time and temperature changes. A special internal structure in kevlar (non magnetic) was preferred to the standard steel one.

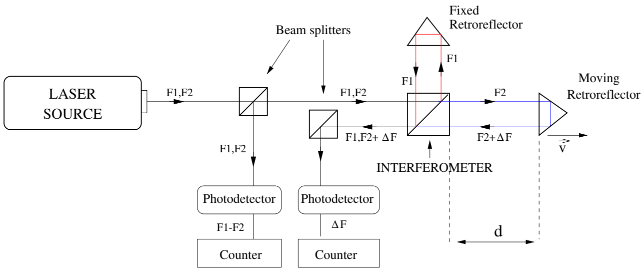


Figure 3: Laser interferometer diagram.

## 3.2 *Displacement Measuring Interferometer*

An accurate position monitoring is needed to evaluate the total integral field according to Eq. 3. For this purpose a laser source was adopted in order to perform a linear interferometer distance measurement. The diagram of the system is shown in Fig. 3.
The laser tube uses a helium-neon source which emits light with a well known and stable wavelength ($\lambda$ =632.8 nm). A detailed description of the system and its relative performances can be found in [5].

## 3.3 *Magnetic field monitoring*

The aim of a mapping is to evaluate the total integral magnetic field characteristic of a magnet, including the fringe regions where the field decreases to zero. The NMR probes adopted (Metrolab Probe Head 1072, Range Type 1 and Range Type 2) cover magnetic fields between 0.043 and 0.026 T. The resolution is $1{\cdot}10^{-7}$ T (or 1 Hz). The guaranteed accuracy is better than $\pm 5$ ppm and the relative accuracy better than $\pm 0.1$ ppm in uniform fields [3]. For the fringe field mapping a search coil has been installed on the mole. The coil was realized at CERN and is made of about one thousand turns around a rectangular frame ($2.5\times$ 1 cm). The motion of the mole in the end field region, where the field gradient is high enough, induces a voltage between the coil terminals, being (for each step):

$$\Phi = \frac{\Delta B}{A} \tag{4}$$

where $\Phi$ is the flux, $\Delta B$ the field change between two locations and A the coil area. The mapping procedure was based on the following steps:

- Forward direction:

  double end field map of the non-connection side with two shifted starting positions;

  core map with the two NMR probes;

  double end field map of the connection side with two shifted ending positions.

- Symmetric procedure for the backward direction.

The measurement of the coil area (see Eq. 4) has been carried out off-line ramping the magnet with the coil still in dipole core. To reduce the uncertainty, the coil area has been also calibrated on-line after each map, as explained at the end of the next paragraph.

## 3.4 *Digital Integrator*

The signal induced on the search coil is fed to a digital integrator. The instrument is given with a precision of $1{\cdot}10^{-4}$ of full scale. Its main features are described in [2]. The drift of the integrator was determined before and after each movement of the coil. The sources of the drift are the dependence of the amplifier offset on the temperature, as well as external sources like the stepping motor, the NMR teslameters, the magnet power converter.
To compensate for drift changes in time, the external offset voltage compensation input is connected to a *digital to analog converter (DAC)*. Repeated cycles were performed before each measurement, in order to move the coil only when the drift of the integrator was small enough. To be independent from the absolute accuracy of the integrator, a calibration of the system has been performed after every end-field measurement. The field inside the dipole gap (i.e. limit between "central field" and "fringe field") was in fact precisely known, by the NMR probes installed on the mole. The difference between this value and the "zero field" value was set equal to the integral of the induced coil voltage, divided for the coil area:

$$B_{NMR} - B_0 = \Delta B = \frac{\int u dt}{A} \tag{5}$$

this procedure overcomes all system drifts developing in a time longer than the measurement period (including, for example, possible variation of the coil area).

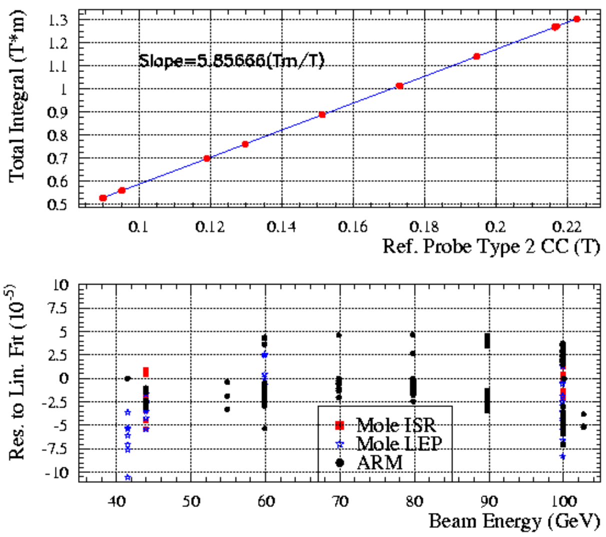


Figure 4: Linear fit integral vs reference probes and residuals.

## 4 MAPPING RESULTS

The travelling mole has been used both in the laboratory and in the LEP tunnel after the transportation of the magnet. The reproducibility of the system in estimating the integral field has been proved to be:

- better than $1 \cdot 10^{-5}$ in the central region (NMRs)
- Few $10^{-5}$ on the total $\int Bdl$

The last figure represent a final result for the LEP spectrometer total integral calibration. They include, the afore mentioned measurements performed in the laboratory by mean of a carbon fiber arm equipped with NMR and Hall probes, the mole measurements in the laboratory and the mole measurements in the LEP tunnel.
Performing a linear fit of all the maps as function of the reference probes readings and calculating the residuals to the fit itself (Fig. 4), provides an estimate of the error in predicting the total B-field integral during the spectrometer operation.

More in detail, the main interest is on the ratio between the integrals at different energies and the quantity

$$\frac{\int B^{E_2} dl}{\int B^{E_1} dl} - \frac{f(B^2_{ref})}{f(B^1_{ref})} \tag{6}$$

leads to the estimate of the error without possible systematic energy dependences.
The data analysis proved that the average value of such difference is in the order of $3{\cdot}10^{-5}$.

## 5 CONCLUSIONS

The LEP spectrometer dipole magnet has been first mapped in the laboratory with a movable arm carrying an NMR probe and two hall probes for the fringe fields. Such a setup provided a large number of measurements, scanning the different accessible parameters, like the cooling water temperature and slightly different magnet conditioning.
The *Mole* system reached the aim of cross-checking the the first method (carbon arm) used in the laboratory to investigate the spectrometer magnet properties.
The measurements showed a high reproducibility of the system and the agreement between the two mapping methods gives an estimate of the total integral field with the aimed accuracy of $3{\cdot}10^{-5}$. It was thus observed that no changes in the magnetic field integral are evident after the magnet transportation and alignment in the LEP tunnel.

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