The LEP Spectrometer Dipole Re-Mapping

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Abstract

The LEP Energy Spectrometer has been successfully operational in the last two years of LEP run as an additional tool for beams energy calibration. Electrons and positrons are bent in an iron-core dipole magnet and accurately monitored by six Beam Position Monitors (BPM). The knowledge of the dipole integral bending field with high accuracy is essential to determine the beam energy. The spectrometer dipole was first mapped in 1999, before its installation in the LEP tunnel, using NMR and Hall probes mounted on a carbon fiber arm. After its installation in the LEP tunnel, the dipole was then re-mapped using NMR and search coil mounted on a mole moving inside the vacuum chamber. The total integral Bdl was thus determined with a relative accuracy of about 3*10-5. Following the closure of LEP the spectrometer dipole was installed in a new magnetic measurements laboratory. A complete re-mapping campaign has been launched to verify the integral Bdl and check possible changes from the previous set of measurements. Improved Hall probes have been used for the new measurement set up. A complete description of the re-mapping set up is presented. Intrinsic accuracy of the measurements and comparison with the first campaign is discussed.

A summary of the work done will be followed by a copy of the slides presented during the workshop.
A detailed description of the LEP Spectrometer Project and of the first mapping campaign can be found in [3].

Summary

The LEP spectrometer has been conceived to be an alternative method for the beam energy determination, providing a *direct* energy measurement. The concept consists in detecting the change in the bending angle θ through the beam position monitors (BPM) and evaluating the total integral B-field seen by the particles while traveling inside the spectrometer magnet. The beam energy is then calculated, being

$$\Delta\theta \propto \frac{\int_L B dl}{E_{beam}} \tag{1}$$

The required accuracy on the extrapolation of the beam operational energy is $1 \cdot 10^{-4}$ (relative error), i.e. 10 MeV for a beam energy of 100 GeV . In order to fulfill such requirements, the integral magnetic field of the dipole magnet has to be determined with a relative accuracy of $3 \cdot 10^{-5}$, while the orbits on both sides of the magnet has to be measured with an accuracy of $5 \div 7 \cdot 10^{-5}$. With the BPM placed on both sides of the magnet along arms of 7 m each, the required accuracy on the beam position is of the order of $1 \cdot 10^{-6}$ m.

The MBI magnet is a C-shaped iron laminated magnet 5.75 m long. The yoke is built from 1.5 mm thick laminations made of low carbon steel, two end plates (30 mm thick) keep the laminations stacked together. Some 20 mm thick steel rods are placed along the longitudinal dimension of the magnet, connecting the end plates. These rods provide a stabilization against twist. Two racetrack shape coils surround the higher and lower pole of the magnet, they are composed of 3 layers, with 6 windings each. The layers are connected electrically in series and hydraulically in parallel. This scheme ensures the same current in every winding and a low temperature across the coil cross section.
The coil heads contain the layer to layer transition and the 6 tails for hydraulic and electrical connections. Tests on the existing injection magnets show that the rigidity of such magnet was not sufficient. The twist along the longitudinal axis was up to two degrees, when wrongly supporting the magnet. In order to avoid changes of the magnetic field shape, caused by internal stress, displacement of the laminations or changes in the magnet dimensions, a special support ("girder") was constructed.
The girder was mounted before the beginning of any of the field mappings, including in such a way in the measurements some possible effects on the field strength and distribution.

The magnet has been measured in 1999, first in the laboratory and then in the LEP tunnel after its installation in the proximity of IP3. In the laboratory the measurements have been performed with two independent systems: a moving carbon fiber arm [1] (equipped with Hall probes and NMR probes) and a traveling mole [2] (equipped with NMR probes and a search coil). The latter method was transportable and therefore used for the magnet mapping in the LEP tunnel. The results of the two mapping campaigns agree within $3 \cdot 10^{-5}$, in terms of total integral field for different values of the excitation current.

The dipole magnet has been placed in a new laboratory after its operation during the last two years of LEP run. Aligned to the ancient carbon fiber arm setup, the magnet has been re-mapped.
The bench setup is described in [1]. Few modifications have been applied to the system. The Hall sensors have been replaced by a new generation of probes, the Siemens KSY 44.
As in the previous campaigns, the measurement procedure included a systematic conditioning of the magnet (Degaussing cycles and Bending Modulation) in order to minimize errors due to the remanent field.
The Hall sensors have been calibrated in the magnet core by mean of the NMR probe, thus calculating

the polynomial transfer function between voltage and magnetic field. Since the probes showed a drift in offset and gain, a systematic calibration has been performed for every map by mean of the field measured in the magnet core by the NMR probes and the known zero-field outside the magnet.

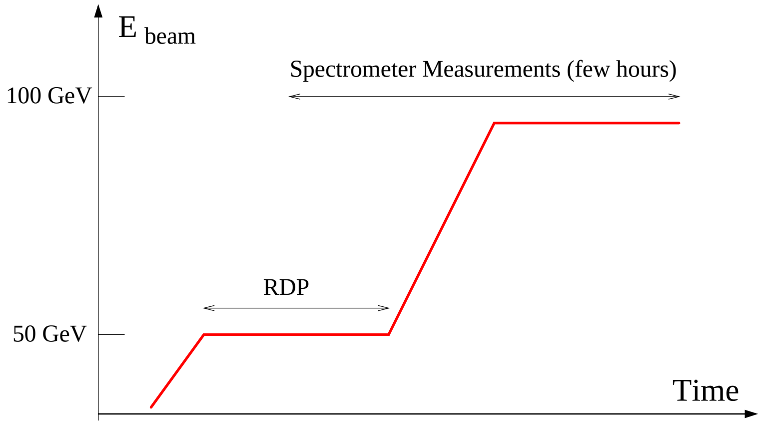
The re-mapping campaign showed results with an excellent reproducibility (around $1.5 \cdot 10^{-5}$) over all the scanned excitation currents).
The comparison with the previous set of measurements results in a relative difference of around $7 \cdot 10^{-5}$ on the total $\int_L B \cdot dl$. Such difference is reduced to around $3 \cdot 10^{-5}$ on the ratios between integrals at different excitation levels.
The causes of such differences are under investigation and the possibility of misalignment between monitors and magnet or between the monitors (distance between the Hall probes on the arm) are being considered.

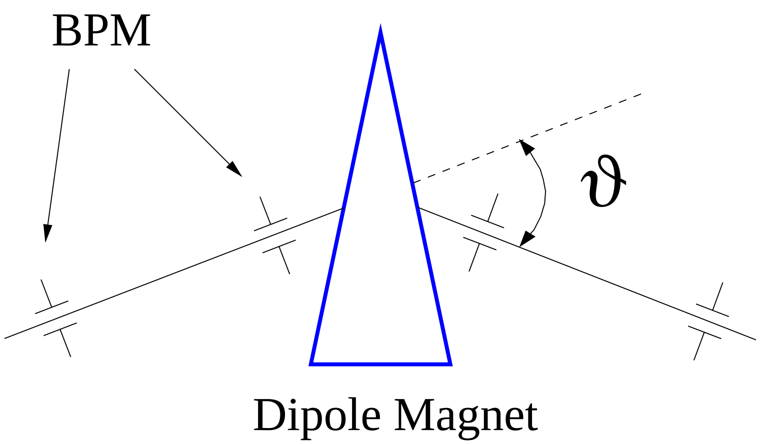
References

[1] "Field Map of the LEP Spectrometer With A Moving Carbon Fiber Arm", D.Cornuet, Proceedings of IMMXI, Brookhaven 1999
[2] "High Accuracy Field Mappings with a Laser Monitored Travelling Mole" F.Roncarolo et al., Proceedings of IMMXI, Brookhaven 1999
[3] "High Accuracy Magnetic Field Mapping of the LEP Spectrometer Magnet", F.Roncarolo, Thesis,
@ http://lepecal.web.cern.ch/LEPECAL/reports/thesis/federico_thesis.pdf.gz

Contents

The LEP Spectrometer





- Evaluate the Ratio between two energies
- Prediction of the LEP beam energy with a relative accuracy of $1 \cdot 10^{-4}$
- The Beam Energy is depending on the Bending Angle and the Total Integral B-field:

$$\boxed{E_{beam} \propto \frac{\int_L Bdl}{\Delta\theta}}$$

- Main elements:
  - Beam Position Monitors (BPM) $\rightarrow$ $\Delta\theta$
  - Bending Magnet mapping $\rightarrow$ $\int_L Bdl$
- $\boxed{\frac{\Delta E}{E} \approx 1 \cdot 10^{-4}}$, $\boxed{\frac{\Delta(\int_L B \cdot dl Ratios)}{\int_L B \cdot dl Ratios} \approx 3 \cdot 10^{-5}}$

The Spectrometer Dipole

- Iron-Core Dipole 5.75 m long, manufactured by industry and assembled at CERN
- Core Field = 0.225 T @ I = 500 A
- C Shaped Gap 100 mm high
- Total Weight (Core + Girder) = 10.3 t
- Independent Temperature Regulated Cooling System (stabilized to $\pm .2\,^{\circ}C$)
- 4 Reference NMR Probes (Metrolab) permanently installed in the gap

Measurement Setup I

- Before Spectrometer Operation

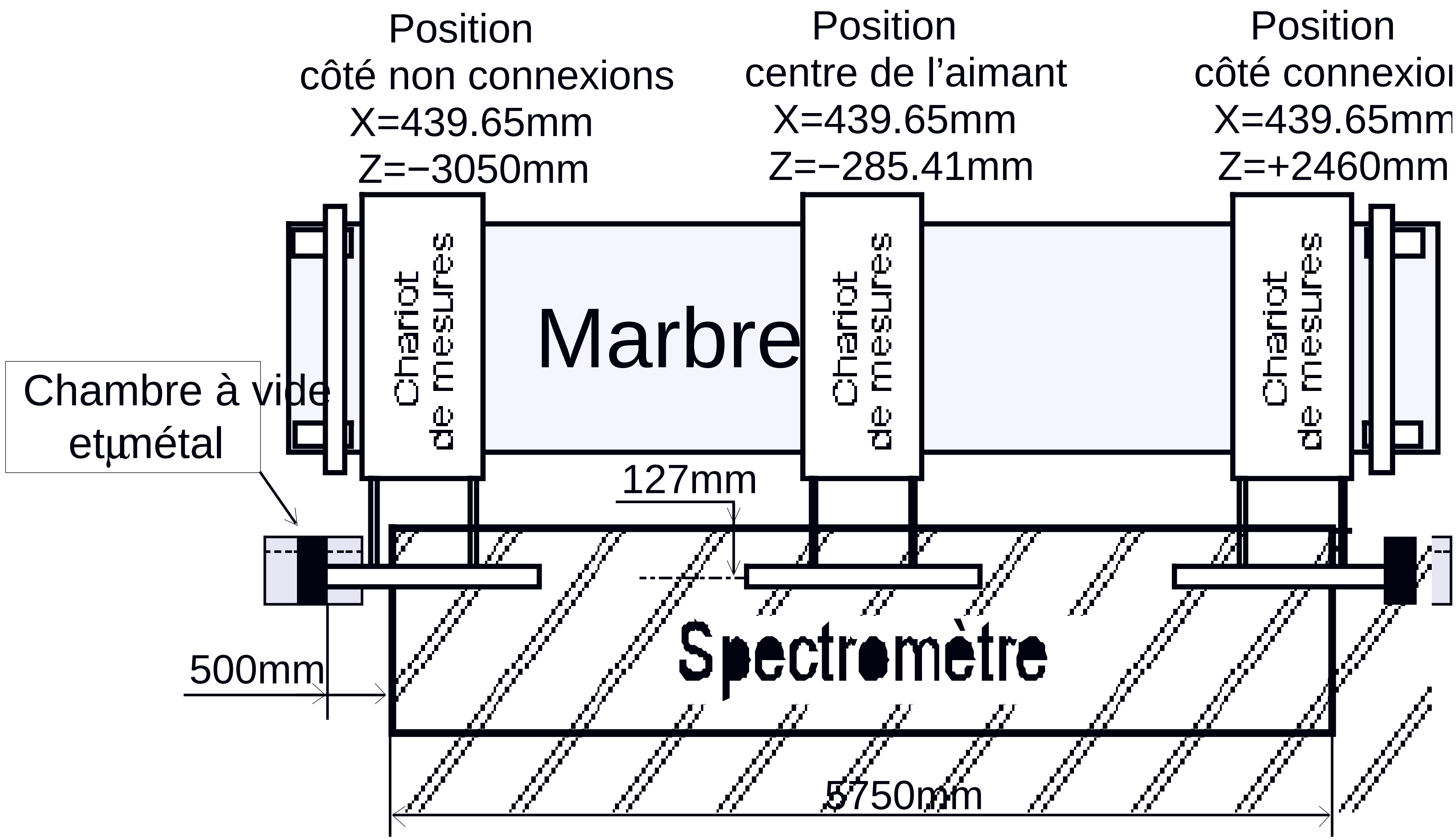
  "Field Map of the LEP Spectrometer With A Moving Carbon Fiber Arm" D.Cornuet, Proceedings of IMMXI, Brookhaven 1999

  "High Accuracy Field Mappings with a Laser Monitored Travelling Mole" F.Roncarolo et al., Proceedings of IMMXI, Brookhaven 1999

- After Spectrometer Operation:
  Re-assembly of the Carbon Fiber Arm measurement bench in a new hall

- Carbon Fiber Arm 2 m long
- Marble (High thermal inertia, 6000 kg)
- Optical Ruler
  (Heidenhain, accuracy $\pm 5\mu m/m, C_t \approx 8 \cdot 10^{-6}/°C$)
- Magnetic Field Monitors (one NMR probe, two Hall Probes)

Measurement Setup II



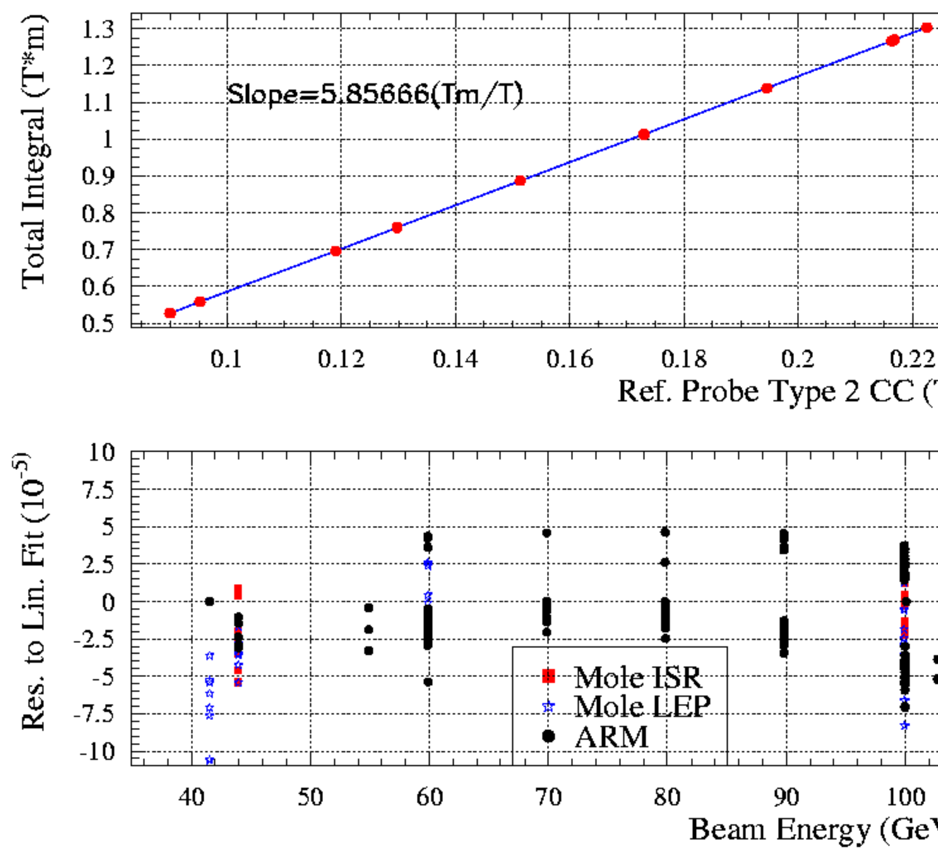
Previous Mapping Campaigns

- Laboratory Measurements 1999 (Carbon-Fiber-Arm and Travelling Mole)
- LEP Tunnel Measurements 1999 (Travelling Mole)
- Final results within the requirements:

$$\frac{\int_L B \cdot dl - f(B_{ref})}{\int_L B \cdot dl} \approx 3 \cdot 10^{-5}$$

- Calibration for the 1999-2000 LEP runs

$$B_{ref} \implies \int_L B \cdot dl$$



System Upgrades

The Hall Probes have been replaced by the sensors Siemens KSY 44

- Metal Organic Vapor Phase Epitaxy Hall sensor
- Built in an extremely flat plastic package (SOH)
- Integrated chip $0.35 \times 0.35\,mm$

Absolute Maximum Ratings

Parameter	Symbol	Limit Values	Unit
Operating temperature	T_A	$-40 \ldots +175$	°C
Storage temperature	T_{stg}	$-50 \ldots +180$	°C
Supply current	I_1	10	mA
Thermal conductivity	G_{thA}	≥ 1.5	mW/K
soldered, in air	G_{thC}	≥ 2.2	mW/K

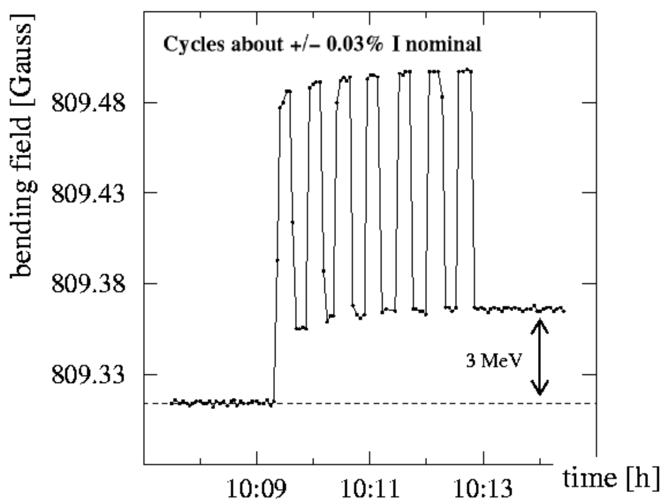
Electrical Characteristics ($T_A = 25\,°C$)

Nominal supply current	I_{1N}	7	mA
Open-circuit sensitivity	K_{B0}	$150 \ldots 265$	V/AT
Open-circuit Hall voltage $I_1 = I_{1N}$, $B = 0.1$ T	V_{20}	$105 \ldots 185$	mV
Ohmic offset voltage $I_1 = I_{1N}$, $B = 0$ T	V_{R0}	$\leq \pm 15$	mV
Linearity of Hall voltage	F_L		
$B = 0 \ldots 0.5$ T		$\leq \pm 0.2$	%
$B = 0 \ldots 1.0$ T		$\leq \pm 0.7$	%
Input resistance $B = 0$ T	R_{10}	$600 \ldots 900$	Ω
Output resistance $B = 0$ T	R_{20}	$1000 \ldots 1500$	Ω
Temperature coefficient of the open-circuit Hall voltage $I_1 = I_{1N}$, $B = 0.1$ T	TC_{V20}	~ -0.03	%/K
Temperature coefficient of the internal resistance, $B = 0$ T	$TC_{R10,\,R20}$	$\sim +0.3$	%/K
Temperature coefficient of ohmic offset voltage, $I_1 = I_{1N}$, $B = 0$ T	TC_{VR0}	~ 0.3	%/K
Inductive zero component, $I_{1N} = 0$	A_2 [1]	0.16	cm^2
Switch-on drift of the ohmic offset	dV_0 [2]	≤ 0.3	mV
voltage $I_1 = I_{1N}$, $B = 0$ T	ΔV_0 [3]	≤ 0.1	mV
Noise figure	F	~ 10	dB

Measurement Procedures & Strategies

Procedures

- Same schema as in the past, including:
  - Degaussing Cycles
  - Ramp
  - Bending Modulation



Bending Modulation

Strategies

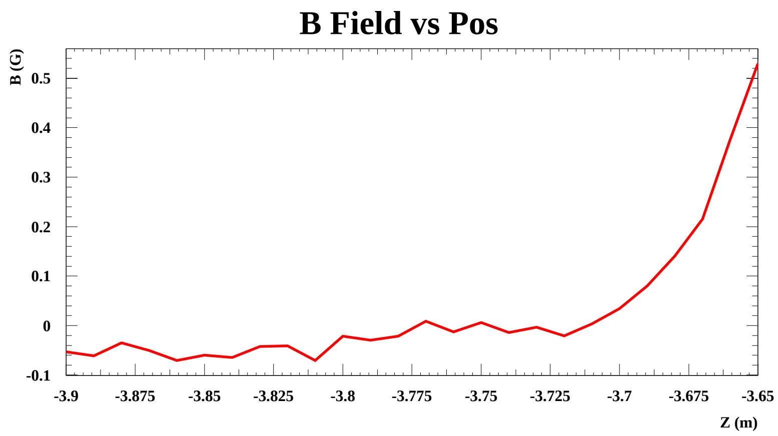
- Scans at different excitation currents in order to check the linearity of $\int_L B \cdot dl$ with respect to the local field measured with the reference NMRs
- Series of maps at two energy levels with ramp in between, in order to reproduce the Spectrometer operation

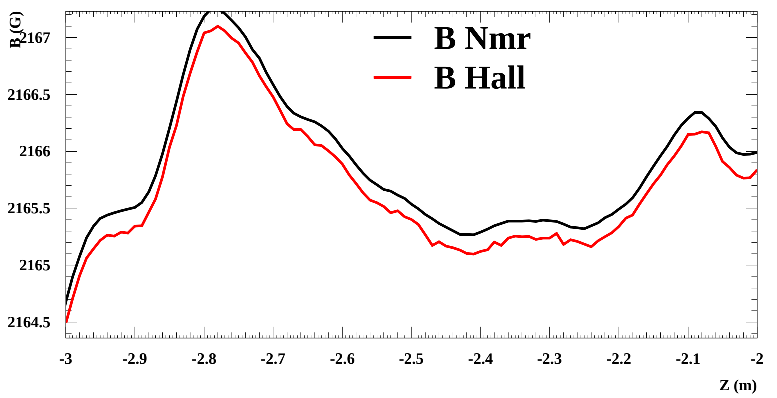
Hall Probes Calibration I

- Off-line Calibration has been performed by mean of the NMR probes
  ➡ Polynomial approximation of the transfer function

$$\boxed{V_{hall}\,[V] \longrightarrow B_{hall}\,[T]}$$

- Hall sensors drift in offset and gain



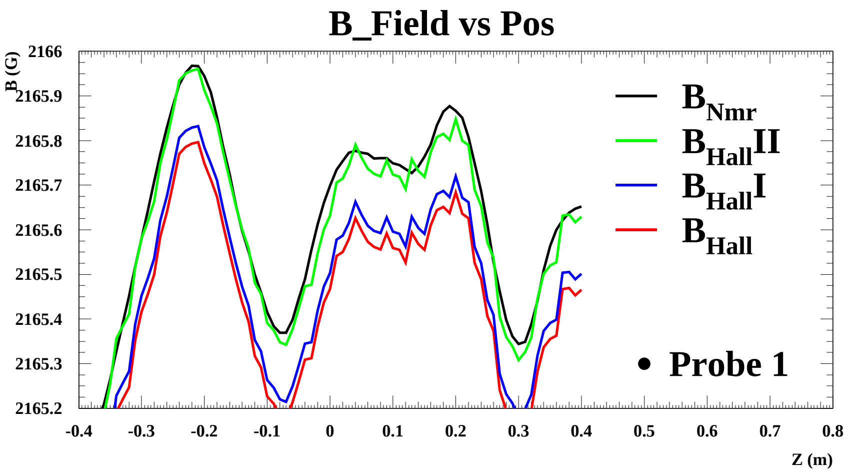


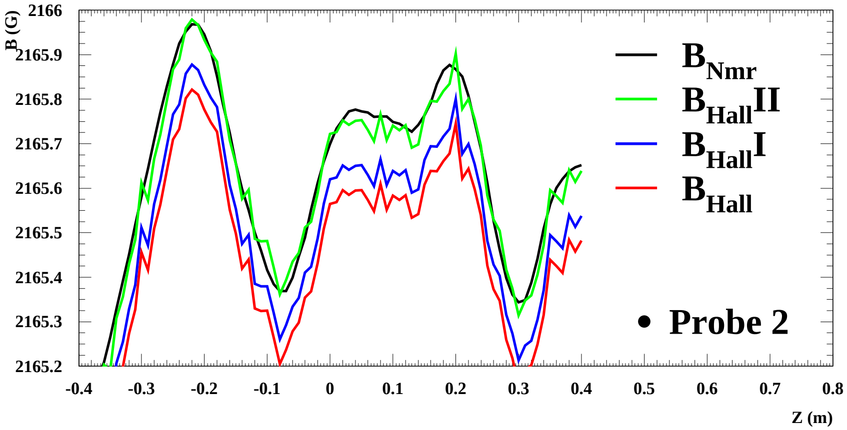
Hall Probes Calibration II

On-Line Calibration

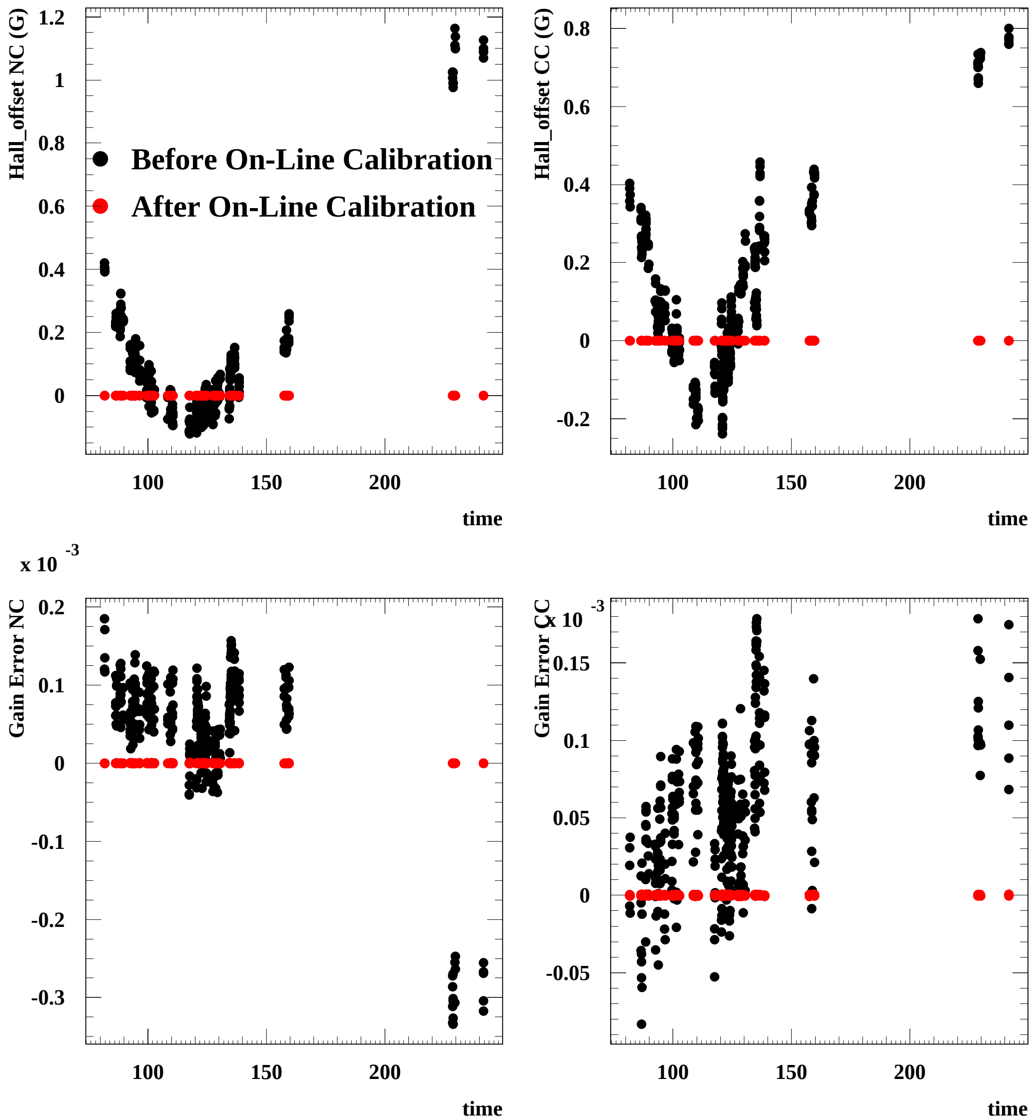
Correction for the Hall Probes Offset and Gain by mean of the known "zero field" in the μ-metal region and "Core Field" read by the NMR Probe.

$$
\begin{aligned}
B_{hall} &= B_{offs} + g \cdot B_{nmr} \\
B^{I}_{hall} &= B_{hall} - B_{offs} \\
B^{II}_{hall} &= \frac{B_{hall} - B_{offs}}{g} \quad (\Leftarrow \; B_{nmr})
\end{aligned}
$$





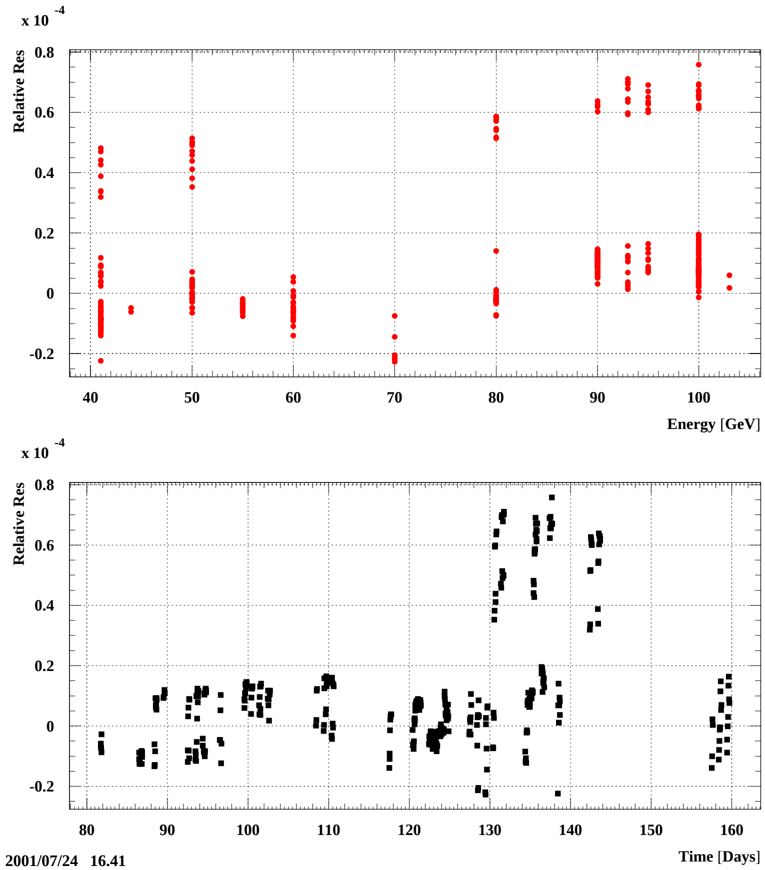
Hall Probes Calibration III



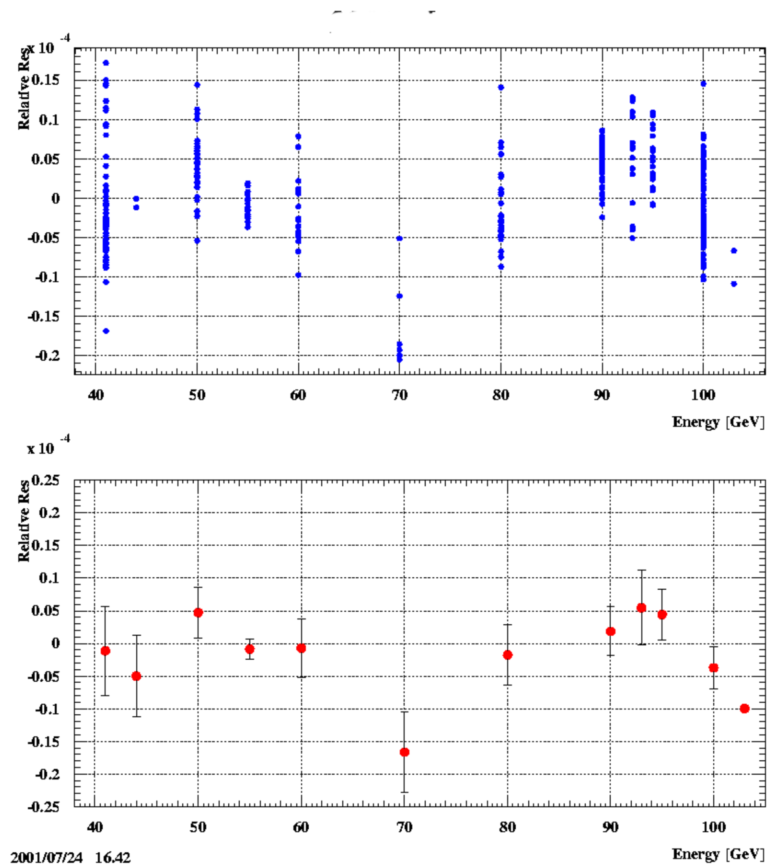
$$Hall_{Offset} = \langle B_{Hall} \rangle_{\mu_{metal}}$$

$$Gain_{Error} = 1 - \frac{B_{Hall}}{B_{Nmr}}$$

Reproducibility of the Re-Mapping Measurements

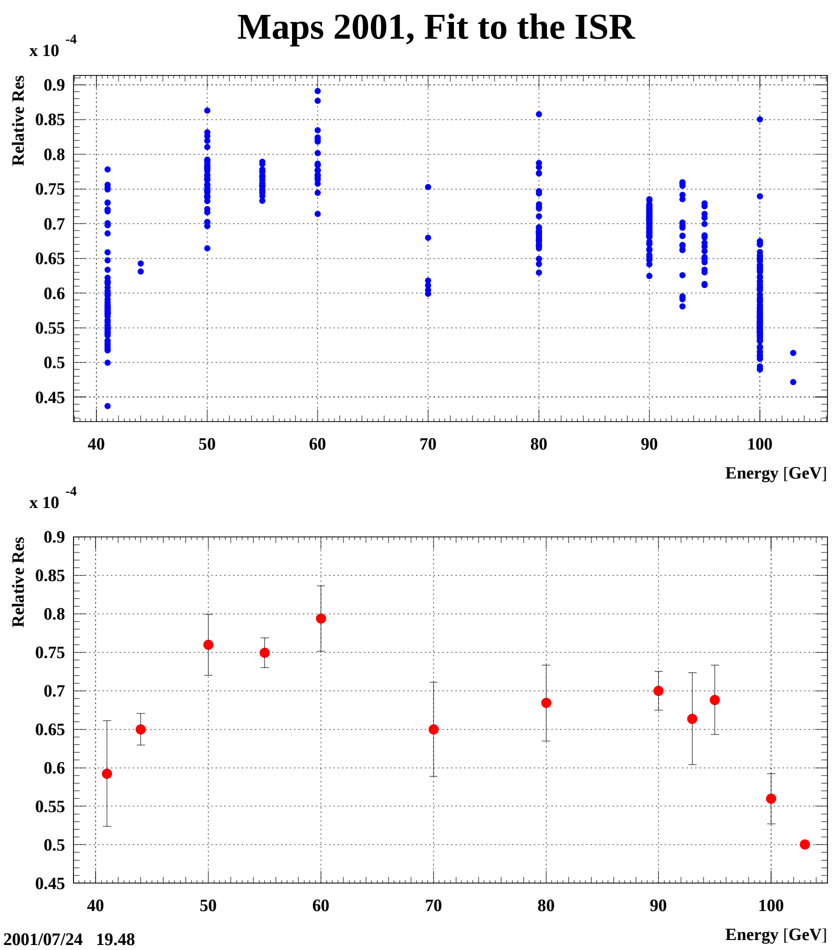


All maps, relative residuals to linear fit (local vs integral field) as function of Beam Energy and Time



Residuals after Temperature Correction

Mapping/Re-mapping Comparison



- Residuals of linear fit using the first mapping c
paign calibration:

$$\int_L B \cdot dl|_{predicted} \;=\; f(B_{local}) = a \cdot B_{local} + b$$

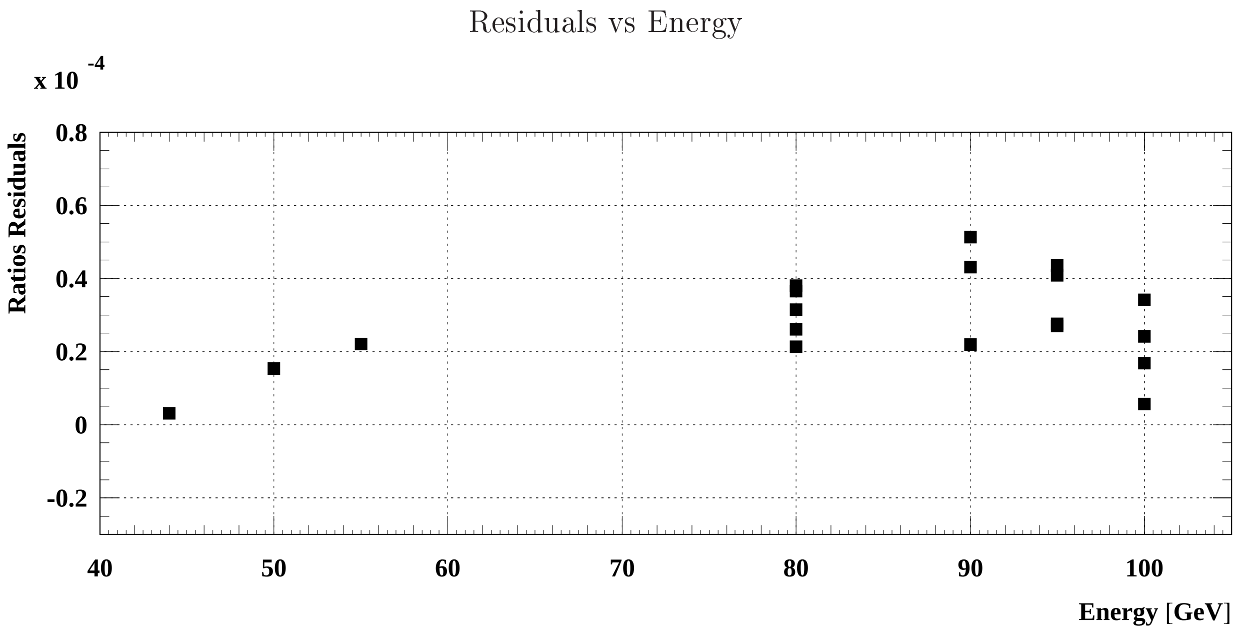
a, b from mapping campaign
(carbon-fiber-arm + Mole)

$$Residual \;=\; \frac{\int_L B \cdot dl|_{re-mapping} - \int_L B \cdot dl|_{predict}}{\int_L B \cdot dl}$$

- Energy Dependence

- Mean Relative Residual $\boxed{\approx 7 \cdot 10^{-5}}$
→ Total $\int_L B \cdot dl$ variation between the
mapping campaigns

Ratios

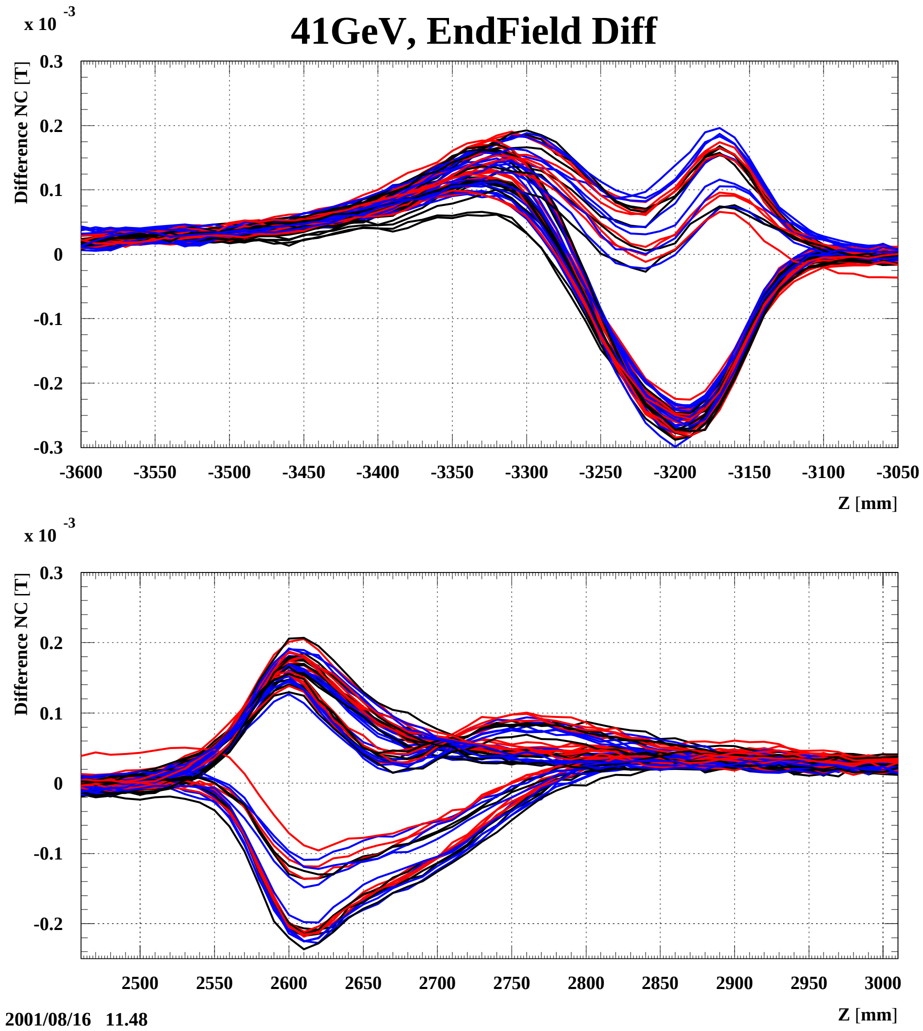


$$Residuals = \frac{\int_L B \cdot dl|^{E_2}}{\int_L B \cdot dl|^{E_1}} - \frac{\int_L B \cdot dl|^{E_2}_{predicted}}{\int_L B \cdot dl|^{E_1}_{predicted}}$$

- Prediction always done using the first mapping calibration
- $E_1 = 41.6\,\mathrm{GeV}$
- $E_2 = 50,\ 55,\ 80,\ 90,\ 95,\ 100\,\mathrm{GeV}$
- Energy Dependence of total $\int_L B \cdot dl$ residuals

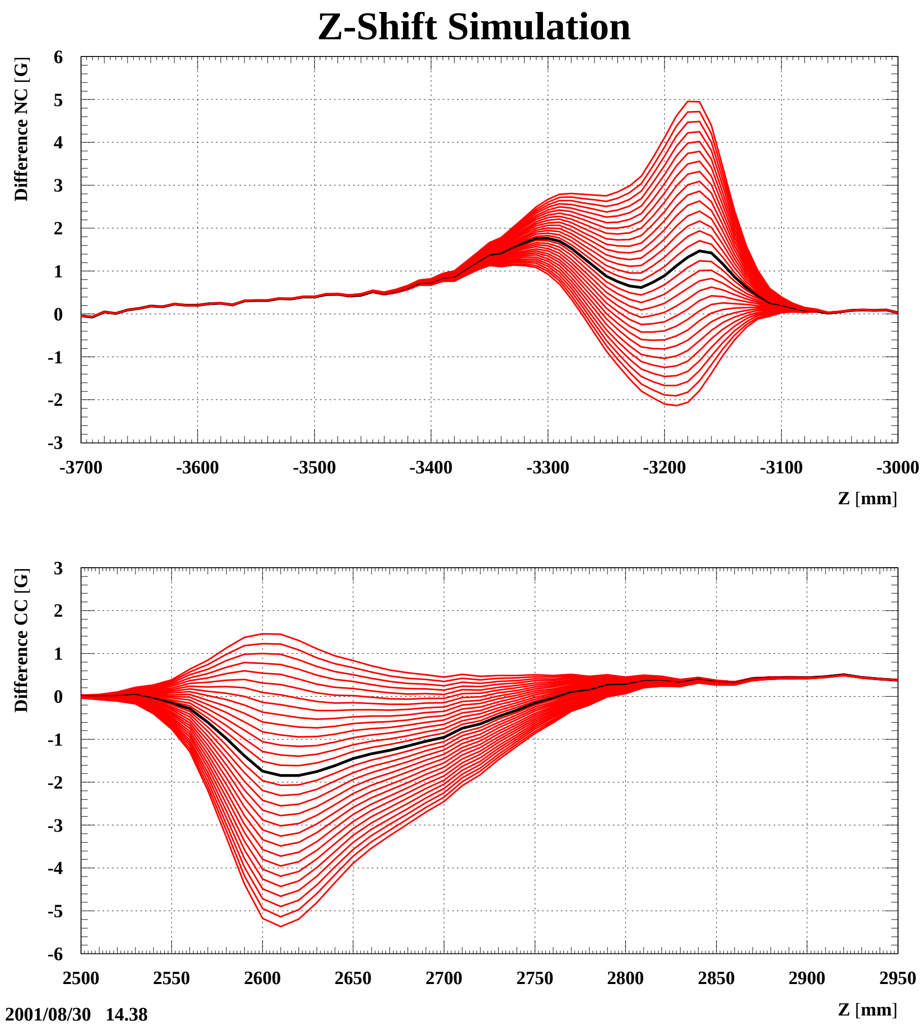
$\Longrightarrow$ Ratio Residuals $\neq 0$

End Field Investigations I



- Differences between local field values (Mapp ReMapping)
- Zoom in the two end-field regions with maximum g ent
- Integral of such differences corresponds to $\approx 7 \cdot$ relative to the total $\int_L B \cdot dl$
- Field differences change shape in time
- Differences variations of the two endfields regions correlated

End Field Investigations II



- Simulation to look for possible causes of local field differences
- Assumption of wrong correlation Field-Position
- Scan between $\pm.5\,mm$
- Possible causes of error:
  - Misalignment Marble-Magnet
  - Misalignment Marble-Ruler
  - Ruler Non-linearities
- Measured differences fit inside simulations

Conclusions

- The integral field of the Spectrometer Dipole Magnet has been measured before its installation in the LEP tunnel in order to produce a calibration local field $\rightarrow$ integral field
- A Re-mapping Campaign was necessary to check field variation during the Spectrometer operation
- The measurement system (equipped with new Hall Probes) shows a reproducibility of $\approx 2 \cdot 10^{-5}$ (relative) when collecting all the results of the re-mapping
- The total $\int_L B \cdot dl$ changed of a factor $7 \cdot 10^{-5}$ (relative)
- Ratios between the total integrals at high and low energies changed of a factor $3 \cdot 10^{-5}$ (relative)
- Possible causes for this changes are under investigation