A Strategy for Series Magnetic Measurements of the LHC Magnets

S. Sanfilippo, L. Bottura and L. Walckiers for the LHC-MTA group.

1. Introduction
   * LHC and magnets for the LHC
   * Field quality errors

1. Tolerances for key beam parameters
2. Target field quality for series production
3. Strategy for Series Measurements
   * 3 levels of control
   * series measurements plan at CERN

1. Equipment/Magnetic measurement system
2. Conclusions
**Introduction**

**Choices for the LHC**

- Proton collider.
- Injection: 450 GeV, collision 7 TeV.
- Superconducting magnet technology (1.9 K).
- Focusing Defocusing (FODO) lattice.
- High luminosity insertions.

**Some machine parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>0.45</td>
</tr>
<tr>
<td>Dipole field</td>
<td>8.36</td>
</tr>
<tr>
<td>Number of dipole magnets</td>
<td>1232</td>
</tr>
<tr>
<td>Number of quadrupole magnets</td>
<td>430</td>
</tr>
<tr>
<td>Number of corrector magnets</td>
<td>about 8000</td>
</tr>
<tr>
<td>Luminosity</td>
<td>10^{34} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>Coil aperture</td>
<td>56 mm</td>
</tr>
<tr>
<td>Distance between apertures</td>
<td>194 mm</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>10^{11}</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2835</td>
</tr>
</tbody>
</table>
Introduction

Each LHC arc = 23 cells

Magnet System: Bending + Focusing / Defocusing + Correctors

Dipole Quadrupole MCS MCDO

LHC Cell - Length about 110 m (schematic layout)
Magnets for the LHC

LHC Main Dipoles (~1232)

- Nominal operating field: 8.33T
- Nominal quench field: 9.76T
- Coil aperture: 56 mm
- Magnetic Length: 14.3 m
- Nominal operating current: 11800 A
- Self Inductance: 100 mH
- Stored energy at 8.33 T: 7 MJ
- Operating temperature: 1.9 K

**Inner Layer Cable**
- No. of strands / cable width: 28 / 15.1 mm
- Strand diameter: 1.065 mm
- NbTi filament diameter: 7 µm
- Cu/NbTi: 1.6

**Outer Layer Cable**
- No. of strands / cable width: 36 / 15.1 mm
- Strand diameter: 0.825 mm
- NbTi filament diameter: 6 µm
- Cu/NbTi: 1.9
## Magnets for the LHC

### LHC Short Straight Section (MQ+correctors) ~400 SSS

**Parameter List of LHC Main Quadrupoles**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated gradient</td>
<td>690 T</td>
</tr>
<tr>
<td>Nominal temperature</td>
<td>1.5 K</td>
</tr>
<tr>
<td>Nominal gradient</td>
<td>225 T/m</td>
</tr>
<tr>
<td>Margin on load line</td>
<td>19.7 %</td>
</tr>
<tr>
<td>Nominal Current</td>
<td>15,000 A</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>3,110 mm</td>
</tr>
<tr>
<td>Beam separation distance (cold)</td>
<td>144.0 mm</td>
</tr>
<tr>
<td>Inner coil aperture diameter (warm)</td>
<td>96.6 mm</td>
</tr>
<tr>
<td>Outer coil diameter</td>
<td>118.6 mm</td>
</tr>
<tr>
<td>Outer yoke diameter</td>
<td>452 mm</td>
</tr>
<tr>
<td>Cellar material</td>
<td>Stainless steel</td>
</tr>
<tr>
<td>Yoke material</td>
<td>Low carbon steel</td>
</tr>
<tr>
<td>Yoke length including end plates</td>
<td>3250 mm</td>
</tr>
<tr>
<td>Number of turns per coil (pole)</td>
<td>24</td>
</tr>
<tr>
<td>Cable length per pole</td>
<td>160 m</td>
</tr>
<tr>
<td>Cable length per two in one quadrupole</td>
<td>1380 m</td>
</tr>
<tr>
<td>Cable width</td>
<td>15.10 mm</td>
</tr>
<tr>
<td>Cable thickness, bare</td>
<td>1.362/1.598 mm</td>
</tr>
<tr>
<td>Insulation thickness axial/axial, compressed</td>
<td>0.11/0.13 mm</td>
</tr>
<tr>
<td>(all polyimide)</td>
<td>radial</td>
</tr>
<tr>
<td>Number of strands</td>
<td>36</td>
</tr>
<tr>
<td>Diameter of strand</td>
<td>0.825 mm</td>
</tr>
<tr>
<td>Cable inner pitch length</td>
<td>100 mm</td>
</tr>
<tr>
<td>Cu/SC ratio</td>
<td>1.9</td>
</tr>
<tr>
<td>Number of filaments in strands</td>
<td>6390</td>
</tr>
<tr>
<td>Filament diameter</td>
<td>6 µm</td>
</tr>
<tr>
<td>Filament twist pitch length</td>
<td>25 mm</td>
</tr>
<tr>
<td>Self-inductance, one aperture</td>
<td>5.6 mH</td>
</tr>
</tbody>
</table>

**Legend**

- **MX**: MQT, MQS, MO,
- **MSCB**: orbit corrector (h and v), MS, MSS
Magnets for the LHC

Correctors

- **Lattice:**
  - MQTL
  - MQT
  - MQS
  - MQSX
  - MQSX A
  - MS
  - MSS
  - MO

- **Orbit (H&V):**
  - MCB
  - MCBC
  - MCBR
  - MCBY
  - MSCB
  - MCBX
  - MCBXA

- **Multipole:**
  - MCD
  - MCO
  - MCS
  - MCOX
  - MCSX
  - MCTX
  - MCOSX
  - MCSSX

See talk by F. Patru for all the details
Magnets for the LHC

Correctors (cont)

LHC Main Dipole Correctors:

**TYPE A**

<table>
<thead>
<tr>
<th>Main Dipole Circuit, 13kA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nested b4/b5 Correctors</td>
</tr>
<tr>
<td>External Aperture</td>
</tr>
<tr>
<td>Internal Aperture</td>
</tr>
<tr>
<td>b3 corrector circuit, ±600A</td>
</tr>
<tr>
<td>b5 corrector circuit, ±600A</td>
</tr>
<tr>
<td>b4 corrector circuit, ±120A</td>
</tr>
</tbody>
</table>

**TYPE B**

<table>
<thead>
<tr>
<th>Main Dipole Circuit, 13kA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-in-one Dipole</td>
</tr>
<tr>
<td>b3 Correctors</td>
</tr>
<tr>
<td>External Aperture</td>
</tr>
<tr>
<td>Internal Aperture</td>
</tr>
<tr>
<td>b3 corrector circuit, ±600A</td>
</tr>
<tr>
<td>b4 corrector circuit, ±120A</td>
</tr>
<tr>
<td>Full circuit</td>
</tr>
<tr>
<td>Spare circuit</td>
</tr>
</tbody>
</table>
Magnets for the LHC

Correctors (cont)

LHC Main Quadrupoles (SSS)

There are 8 separately powered sectors.
- Each sector contains ~46 SSS
  One ‘F’ circuit (both apertures in series)
  One ‘D’ circuit (both apertures in series)
- 2 families of Octupoles per aperture
- 1 family of Skew Sextupoles per aperture
- 1 family of Skew Quadrupoles per aperture
- 2 families of Tuning Quadrupoles per aperture

Needs ~ 42 wires

4 families of Chromaticity Sextupoles

Locally powered orbit correctors

Courtesy P. Proudlock
Magnets for the LHC

LHC insertion magnets

- MQM matching quadrupoles
- MQY quadrupoles
- Separation dipoles (BNL)
- MQXA, MQXB quadrupoles (KEK, FNAL)

Not discussed in this talk.
Dipoles and SSS to be measured.

Integrated deliveries of cryomagnets

- Integral of dipoles deliveries
- Integral of DS. SSS deliveries
- Integral of SSS deliveries
- Total Integral
- Total rate
Superconducting Magnet Tests Plant (SMTP) in SM18 - 12 test benches for cold tests at CERN.

- Dipoles and/or SSS units attached to one of 12 test stations.
- Test capacity: up to 60 magnet tests per month.
- Tests will focus on:
  - quench performance
  - magnet protection
  - magnetic measurements
  - acceptance of cryogenic, insulation vacuum, and electric integrity
Components critical for field quality

- Coil characteristics
- Collars
  - geometry
  - magnetic properties
- Iron yoke and inserts
  - geometry
  - magnetic properties
- “two in one” configuration
- Properties of the NbTi Rutherford cables.
  - magnetisation at 0.5 T controlled within 4.5 %.
  - minimum inter strand resistance of 20 \( \mu\Omega \)
Origins of the field errors

- **winding geometry** (warm and cold, lo-B & hi-B),

- **saturation** (cold, hi-B),

- errors related to the **diamagnetic behaviour of superconducting** strands and cables:
  - **effect of the persistent currents**,  
  - **ramp rate** induced harmonic errors (eddy currents),  
  - **decay of the persistent currents** at injection plateau and **snap-back phenomena** during the following ramp.
Multipole field expansion in the complex plane.

- 2-D plane field in the current-free region of the magnet aperture

\[
B_y + iB_x = \sum_{n=1}^{\infty} C_n \left( \frac{z}{R_{\text{ref}}} \right)^{n-1} = \sum_{n=1}^{\infty} (B_n + iA_n) \left( \frac{z}{R_{\text{ref}}} \right)^{n-1} = |C_m| \sum_{n=1}^{\infty} \left( \frac{b_n + ia_n}{10^4} \right) \left( \frac{z}{R_{\text{ref}}} \right)^{n-1}
\]

Relative to main field (units)
Reference radius (17 mm for LHC)
Beam requirements

LHC machine: Luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

Effect of the field errors:
- unstable transverse particle motion (amplitude growth, larger beam size)
- aperture restrictions $\rightarrow$ beam losses $\rightarrow$ Reduced luminosity Quenches

Beam requirements for the field quality:
- maximize the Mechanical Aperture,
- maximize the Dynamical Aperture,
- beam parameters variations.
**Beam requirements**

*Mechanical aperture:*
- control of the spread of energy $\Delta E/E << 10^{-4}$
- control of the orbit errors

  $\Rightarrow$ **Tolerance on $b_1$**

  $\Rightarrow$ **Tolerance on $b_1, a_1, b_2, a_2$.**

*Dynamical Aperture ($12 \sigma$ max):*
- control of the tune variation $\Delta Q (3.10^{-3})$, the tune coupling ($3.10^{-3}$) and vertical dispersion.
- avoid de-tuning with amplitudes and resonances

  $\Rightarrow$ **Limits on** $b_2, a_2, b_4, a_4$

- control of the chromaticity $\xi = \Delta Q / (\Delta P/P) \approx 1$
  (avoid instabilities, resonances)

  $\Rightarrow$ **Tolerance on $b_3$**

*To keep in mind: the maximum corrector strength at top energy*
- $b_3 < 4$ units
- $b_4 < 0.1$ units
- $b_5 < 0.21$ units

*(source: O. Bruning, SL-AP)*
**Consequences on field quality (units)**

<table>
<thead>
<tr>
<th>multipole</th>
<th>systematic</th>
<th>uncertainty</th>
<th>random</th>
</tr>
</thead>
<tbody>
<tr>
<td>b1</td>
<td>0.3</td>
<td>0.8</td>
<td>0.13</td>
</tr>
<tr>
<td>b2</td>
<td>0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a2</td>
<td></td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>b3</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a3</td>
<td></td>
<td>0.17</td>
<td>2.1</td>
</tr>
<tr>
<td>b4</td>
<td></td>
<td>0.07</td>
<td>0.49</td>
</tr>
<tr>
<td>b5</td>
<td>0.18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For a series production:
Systematic = average value (gaussian distribution)
Random = standard deviation $\sigma$ (gaussian distribution)
Uncertainty (in the average) = bias from the expected systematic value.
# Beam requirements

Table 2 Alignment tolerance for the dipole CMA

<table>
<thead>
<tr>
<th></th>
<th>Tolerance</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>systematic (1σ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB</td>
<td>x 0.14 mm</td>
<td>y 0.14 mm</td>
<td>roll 0.5 mrad</td>
</tr>
<tr>
<td></td>
<td>random (1σ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB</td>
<td>x 0.29 mm</td>
<td>y 0.42 mm</td>
<td>roll 0.5 mrad</td>
</tr>
<tr>
<td></td>
<td>Uncertainty (1σ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MB</td>
<td>x 0.47 mm</td>
<td>y 0.29 mm</td>
<td>roll -</td>
</tr>
</tbody>
</table>

(source: W.Scandale, LHC/MMS)

Table 3 Alignment tolerance for the SSS components

<table>
<thead>
<tr>
<th></th>
<th>Error</th>
<th>Tolerance</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>systematic (1σ)</td>
<td>random</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MQ</td>
<td>orbit excursion x</td>
<td>y -</td>
<td></td>
<td>0.37 mm</td>
</tr>
<tr>
<td></td>
<td>orbit excursion</td>
<td>roll 0.3 mrad</td>
<td>1.0 mrad</td>
<td></td>
</tr>
<tr>
<td>MSC</td>
<td>tune/β-beating x</td>
<td>y 0.1 mm</td>
<td></td>
<td>1.0 mm</td>
</tr>
<tr>
<td></td>
<td>coupling</td>
<td>roll 2.0 mrad</td>
<td>1.5 mrad</td>
<td></td>
</tr>
<tr>
<td>MS</td>
<td>chromatic. coupling</td>
<td>x 0.1 mm</td>
<td>y 0.1 mm</td>
<td>0.8 mm</td>
</tr>
<tr>
<td></td>
<td>coupling</td>
<td>roll 2.0 mrad</td>
<td>1.5 mrad</td>
<td></td>
</tr>
<tr>
<td>MO</td>
<td>chromaticity/DA x</td>
<td>y 0.16 mm</td>
<td></td>
<td>1.9 mm</td>
</tr>
<tr>
<td></td>
<td>DA</td>
<td>roll 1.0 mrad</td>
<td>1.5 mrad</td>
<td></td>
</tr>
<tr>
<td>MDC</td>
<td>coupling</td>
<td>roll 0.6 mrad</td>
<td>0.6 mrad</td>
<td></td>
</tr>
</tbody>
</table>

Tight tolerances on alignment.
### Target field quality for series production (Dipoles)

<table>
<thead>
<tr>
<th>Multipoles</th>
<th>Systematic (max value) (units)</th>
<th>Uncertainty (max value) (units)</th>
<th>Random (r.m.s) (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b1</td>
<td>None</td>
<td>6.5</td>
<td>8.0</td>
</tr>
<tr>
<td>a1</td>
<td>6.5 average per arc cell</td>
<td></td>
<td>8.0</td>
</tr>
<tr>
<td>b2</td>
<td>1.4</td>
<td>0.8</td>
<td>0.7 (injection) 0.8 (collision 7 TeV)</td>
</tr>
<tr>
<td>a2</td>
<td></td>
<td>0.9</td>
<td>1.9 (injection) 2.3 (end of ramp) 1.6 (collision 7 TeV)</td>
</tr>
<tr>
<td>b3</td>
<td>-10.7 (injection) 3.0 (collision)</td>
<td>Including bias due to uncertainty</td>
<td>1.4 (injection) 1.8 (collision 7 TeV)</td>
</tr>
<tr>
<td>a3</td>
<td></td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>b4</td>
<td></td>
<td>0.4</td>
<td>0.49</td>
</tr>
<tr>
<td>a4</td>
<td></td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>b5</td>
<td>1.1 (injection) 0.8 (collision)</td>
<td>Including bias due to uncertainty</td>
<td>0.5 (injection) 0.4 (collision 7 TeV)</td>
</tr>
<tr>
<td>a5</td>
<td></td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

*From S.Fartoukh and O.Bruning, LHC Report in press*
Upper(lower) limit: nominal+(-) allowed systematic errors+(-)2* allowed random errors.
How to fill the gap?

- Field quality requirements from beam physics will not be satisfied by the magnets as produced.

- The correction system will fill the gap.

Effective if the field errors are known at operating conditions or beam induced effects can be measured and controlled!

Quality control levels and series measurement plan.
Gap between beam requirements/magnets as produced

- Differences between warm and cold harmonic values.
- Errors related to superconducting cable effects are not controlled.
- Control the effect of the electromagnetic load on odd harmonics.

Geometric errors (warm/cold correlation)

Effect of the Lorentz Force on $b_3$ geometric

Decay for main dipoles compared to expected values (+/- 1 σ bound)

$\sigma = 0.49$ units

$\Delta \xi = 52 \Delta b_3$ (decay)!
Quality control levels

Three control levels

◆ Tolerance control in industry, warm magnetic measurements and alignment in industry
  ■ coil size, collar geometry, iron packs, survey, field quality
    (talks by V.Remondino, J.Garcia, F.Patru)

◆ Warm magnetic measurements and alignment at CERN (before and after cold tests).

◆ Cold magnetic measurements and alignment at CERN (MB, SSS)
  (talks by M.Buzio, N.Smirnov)
**First level of control: Quality Control during Fabrication**

*Interaction with Fabrication process – Magnets at Room temperature*

**MB in Industry (LHC-MMS)**
- Geometry of coils and structures, Field Quality,
- Identify spot major faults (e.g. wrong wedges),
- Alignment of end correctors, control of sagitta,
- Control of the strand magnetization (4.5%) , $R_c$ higher than 20 $\mu\Omega$.

**MQ in Industry (Saclay + LHC-MMS)**
- Warm magnetic measurements, geometrical verifications of components.

**Corrector Magnets (LHC ICP+LHC MTA)**
- Check mainly axis reference points and field direction,
- In Industry with Cern equipment or at Cern.  
  *(talk by F.Patru)*

**....Controls documented in a Quality Assurance Plan**
**TESTS AT CERN**

Tests of the cold masses in warm or cold conditions

Warm re-testing of the cold masses **before cool-down** as a cross-check of factory tests and control of the transportation effect:

- quality of the magnetic field at warm,
- magnetic axis measurements (dipoles+correctors).

**Limited to statistical verifications (10% of the cold masses)**

At this stage the control of the cold properties is not possible:

- deformation during cool down and under e.m. loads,
- iron saturation and superconducting cable effects.

**Field quality measurements at cold are necessary!**
MB SERIES MEASUREMENT PLAN AT CERN

**warm (SMA-18)**
- Warm mole
- 15m shaft
- Warm mole
- Polarity meter

**cold (SM18)**
- Standard cold field tests + QCD: 100%
- Extended cold field tests: 10%
- Cold alignment: 100%
- Warm polarity test: 100%

**Flow of the magnet**

- Standard cold field test ~12h
- Extended cold field test ~42h
- Magnet stripped correctors can be powered

**cold B1**
- Strength calibration: 10%
- Warm polarity test: 100%
- Warm (SMA-18)

**cold field**
- Warm (SMA-18)
- Warm alignment: 10%
- Flow of the magnet
SSS SERIES MEASUREMENT PLAN AT CERN

**cold (SM18)**

- **Scanner**
  - Standard cold field tests 50%
  - 16h 2Q
  - 5 m shafts
- **Scanner**
  - Cold alignment 50%
  - 6 h
- **Stretched wire**
  - Standard cold field tests 50%
  - 10h 1Q
- **Cold gradient & direction calibration**
  - 40%
  - 12h 6 Q
- Flow of the magnet

**warm (SM18)**

- **Mole**
  - Warm alignment 50%
  - 8 h
  - 6 h
- **Polarity meter**
  - Warm polarity test 50%
  - 1 h
- **Scanner**
  - Warm alignment 50%
  - 6 h
  - 1 h
- **Polarity meter**
  - Warm polarity test 50%
  - 1 h

**Cold extended field test**

- 10%
  - 12h 6 Q

**Flow of the magnet**
Roles of warm measurements (at 300 K)

- Warm measurements are necessary as:
  - Verify warm alignment measurements (through combined magnetic/survey measurements),
  - local and integral field, direction and harmonics,
  - Basis for warm-cold correlation on alignment (possibly field and harmonics) $\Rightarrow$ potential for large gain of cold test time.
  - diagnostic after delivery and completion of magnet (monitor displacements/deformations due to shipping and cryostating).

(talks by V.Remondino, J.Garcia, M.Buzio, N. Smirnov)
Role of standard cold measurements

- Magnetic measurements (and alignment for SSS only):
  - Parameters for quantitative field quality model in standard conditions (linear and non-linear effects):
    - geometric
    - eddy
    - decay
    - saturation
    - persistent
  - Effect of the cool down on the deformation of the cold mass and cryostat geometry,
  - thermal contraction and deformation of the feet.

- 100 % testing necessary to:
  - provisional acceptance of the magnets,
  - provide databases for LHC installation, commissioning and operation.
Extended cold measurements

- **Magnetic measurement (and alignment for MB only) performed:**
  - measurements at injection with different powering history,
  - harmonic measurements after quenches and current cycles,
  - measure of the field direction (cold mole)

- **Extended cold tests are necessary to:**
  - determine the scaling laws for non-linear behaviors
    (ex: decay and snap-back as a function of powering history),
  - check the harmonic stability after quenches and after an accelerated life test
    (simulation of the life of the machine),
  - verify alignment of MB and correctors in cold conditions,
  - advance R&D for understanding of magnets.

- **Significant sample: 10% of the population**
Warm alignment after cool down

- Measurement performed for 100% of the dipoles (and associated correctors) and the SSS.

- Measurement performed at the latest possible time before the installation in the tunnel.
  - Identify any movements in the cold masses during cold test (magnetic measurements with rotating coil+QCD, optical measurement of coil rotation center, laser tracker for fiducialisation)
Corrector Magnets

Goals
- Verify magnetic axis/mechanical axis, magnetic field strength, harmonics
- Magnet’s integrity: Nturns, interturns shorts, polarity of connections,
- Width of hysteresis loop (mainly for nested magnets).

Strategy: (tests before being inserted in the dipoles or SSS)
- Tests performed at warm in industry.
- Checks as statistical basis at warm at CERN.
- Cold measurements of 2% to 10% of the magnets.

Tool CERN-built room temperature industry benches
(mechanical bench with rotating measurement coil, integrators, bipolar power supply

Cold test station at CERN.

See F.Patru talk for all the details
Criteria of acceptance for the correctors

Misalignment Magnetic/mechanical axis: 0.1 m rad max
Roll angles: from 1.5 to 2.5 m rad depending on the correctors
Main field strength: maximum spread of 1% around the average
All harmonics: below 1% of the main field at 17 mm radius

See F.Patru talk for all the details
## Target measurements for main dipoles

<table>
<thead>
<tr>
<th></th>
<th>absolute</th>
<th>reproducibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main field and field integral</td>
<td>(-)</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Integral transfer function</td>
<td>(-)</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Main field direction with</td>
<td>(mrad)</td>
<td>0.2</td>
</tr>
<tr>
<td>respect to fiducials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmonics</td>
<td>(units @ 17 mm)</td>
<td>0.01</td>
</tr>
<tr>
<td>Magnetic center with</td>
<td>(mm)</td>
<td>0.15</td>
</tr>
<tr>
<td>respect to fiducials</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: test durations do not include installation*
## Target measurements for main quadrupoles

<table>
<thead>
<tr>
<th>Description</th>
<th>Absolute</th>
<th>Reproducibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main field and field integral</td>
<td>$(-) 5.0 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Integral transfer function</td>
<td>$(-) 5.0 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Main field direction with respect to fiducials</td>
<td>$(mrad) 0.3$</td>
<td>$0.1$</td>
</tr>
<tr>
<td>Harmonics (units @ 17 mm)</td>
<td>$0.05$</td>
<td>$0.01$</td>
</tr>
<tr>
<td>Magnetic center with respect to fiducials</td>
<td>$(mm) 0.15$</td>
<td>$0.15$</td>
</tr>
</tbody>
</table>

*Note: test durations do not include installation*
# Equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Units planned</th>
<th>Procured</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twin rotating coils for main dipoles</td>
<td>7 shaft pairs</td>
<td>2 coils pairs</td>
<td>integral and local field, direction, harmonics in main dipoles</td>
</tr>
<tr>
<td></td>
<td>5 TRU’s</td>
<td>5 TRU’s</td>
<td></td>
</tr>
<tr>
<td>Automated scanners</td>
<td>2</td>
<td>2</td>
<td>integral and local field, direction, harmonics and axis in SSS</td>
</tr>
<tr>
<td>Twin rotating coils for SSS</td>
<td>3 shaft pairs</td>
<td>-</td>
<td>integral and local field, direction, harmonics in SSS</td>
</tr>
<tr>
<td></td>
<td>2 TRU’s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm moles</td>
<td>2 systems</td>
<td>1</td>
<td>relative and absolute alignment of warm main dipoles, SSS and</td>
</tr>
<tr>
<td></td>
<td>1 spare mole</td>
<td></td>
<td>associated correctors</td>
</tr>
<tr>
<td>Cold moles</td>
<td>1</td>
<td>-</td>
<td>relative alignment of cold main dipoles and associated correctors</td>
</tr>
<tr>
<td>Single stretched wire</td>
<td>2</td>
<td>1</td>
<td>relative and absolute alignment of cold SSS and associated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>correctors, cross calibration</td>
</tr>
<tr>
<td>Salamander</td>
<td>1</td>
<td>-</td>
<td>in-situ calibration of integral dipole</td>
</tr>
<tr>
<td>Polarity tester</td>
<td>1</td>
<td>-</td>
<td>strength and direction of main field</td>
</tr>
<tr>
<td>Coil center tracker</td>
<td>3 WRT+2 SRT</td>
<td>1 WRT+1 SRT</td>
<td>x-y position of the coil rotation axis</td>
</tr>
<tr>
<td>Laser tracker</td>
<td>3</td>
<td>1</td>
<td>3-D survey of fiducials on cryomagnets and on measurement systems</td>
</tr>
</tbody>
</table>
Equipment

Situation in April 2001

Test equipment

50 % procured
20 % operational

planned
procured or ordered
operational

Units

MB TRU's
MB long shaft pairs
SSS scanners
SSS TRU's
SSS long shaft pairs
Warm moles
Cold moles
SSW
Salamander
Polarity tester
Trackers
LTD
### Bench calibration equipment

<table>
<thead>
<tr>
<th>Calibration bench</th>
<th>Units planned</th>
<th>Procured</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft</td>
<td>1</td>
<td>1</td>
<td>coil surface and relative sector orientation</td>
</tr>
<tr>
<td>Sector</td>
<td>1</td>
<td>-</td>
<td>coil sector parameters (surface, radius, tilt)</td>
</tr>
<tr>
<td>Warm mole direction</td>
<td>1</td>
<td>-</td>
<td>field direction in warm mole</td>
</tr>
<tr>
<td>Reference quadrupole</td>
<td>1</td>
<td>-</td>
<td>calibration of center and direction of the reference quadrupole field</td>
</tr>
<tr>
<td>Mole axis</td>
<td>1</td>
<td>-</td>
<td>calibration of the axis of warm and cold mole</td>
</tr>
<tr>
<td>telescope/CCD</td>
<td>1</td>
<td>-</td>
<td>calibration of conversion factors to mm for telescope/CCD systems</td>
</tr>
</tbody>
</table>
Bench calibration equipment

Situation in April 2001
Magnetic measurement system and analysis

Talks by H.Reymond (MMP), by M.Gateau (MMP), L.Deniau (DAP).
Conclusions

I. **Magnetic field measurement goal**: verification of the field quality in operating conditions fitting with the accuracy required for commissioning and the operation of the LHC.

II. Accuracy not achieved by industrial control and field measurement in warm conditions only. Warm and cold measurement at CERN are necessary.

III. Test plan proposed with all the tests technically feasible within the time allocated.

IV. Adapted test equipment is procured or in process of procurements.