A Strategy for Series Magnetic Measurements of the LHC Magnets

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1. Introduction

   LHC and magnets for the LHC

   Field quality errors

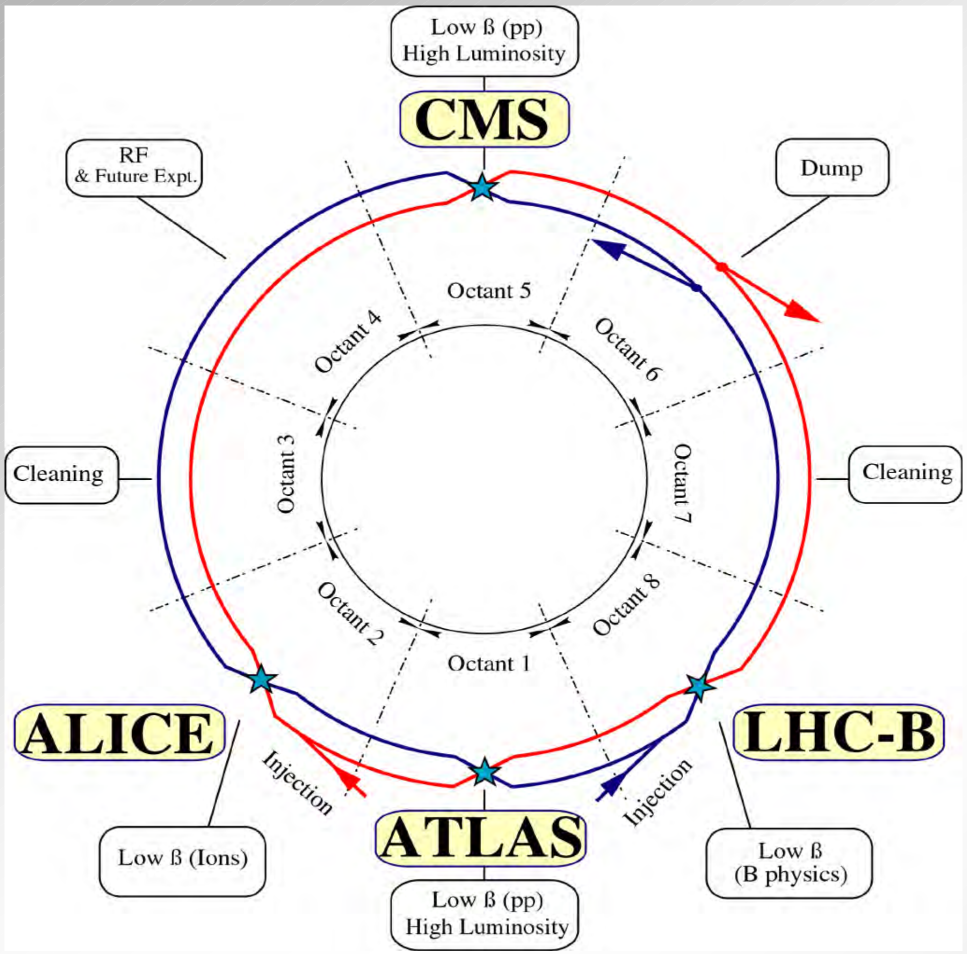
1. Tolerances for key beam parameters
2. Target field quality for series production
3. Strategy for Series Measurements

   3 levels of control

   series measurements plan at CERN

1. Equipment/Magnetic measurement system
2. Conclusions

Introduction



Basic layout of the LHC

Choices for the LHC

- Proton collider.

-Injection:450 GeV,collision 7 TeV.

-Superconducting magnet technology (1.9 K).

-Focusing Defocusing (FODO) lattice.

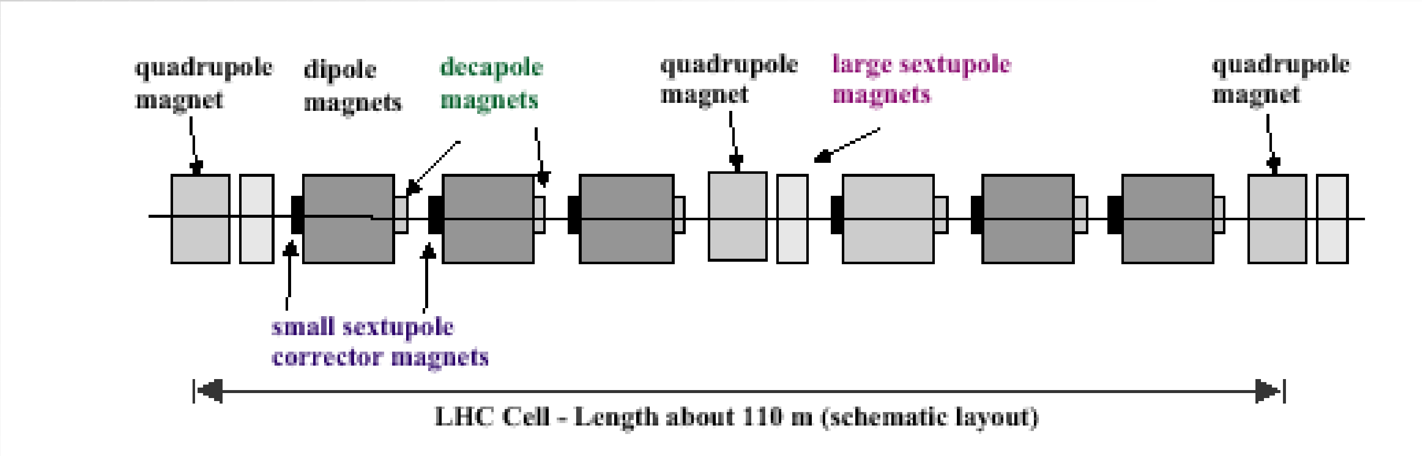
-High luminosity insertions.

Energy	TeV	7
Injection energy	TeV	0.45
Dipole field	Tesla	8.36
Number of dipole magnets		1232
Number of quadrupole magnets		430
Number of corrector magnets		about 8000
Luminosity	$cm^{-2}s^{-1}$	10^{34}
Coil aperture	mm	56
Distance between apertures	mm	194
Particles per bunch		10^{11}
Number of bunches		2835

Some machine parameters.

Introduction

Each LHC arc= 23 cells



Magnet System: Bending + Focusing / Defocusing + Correctors

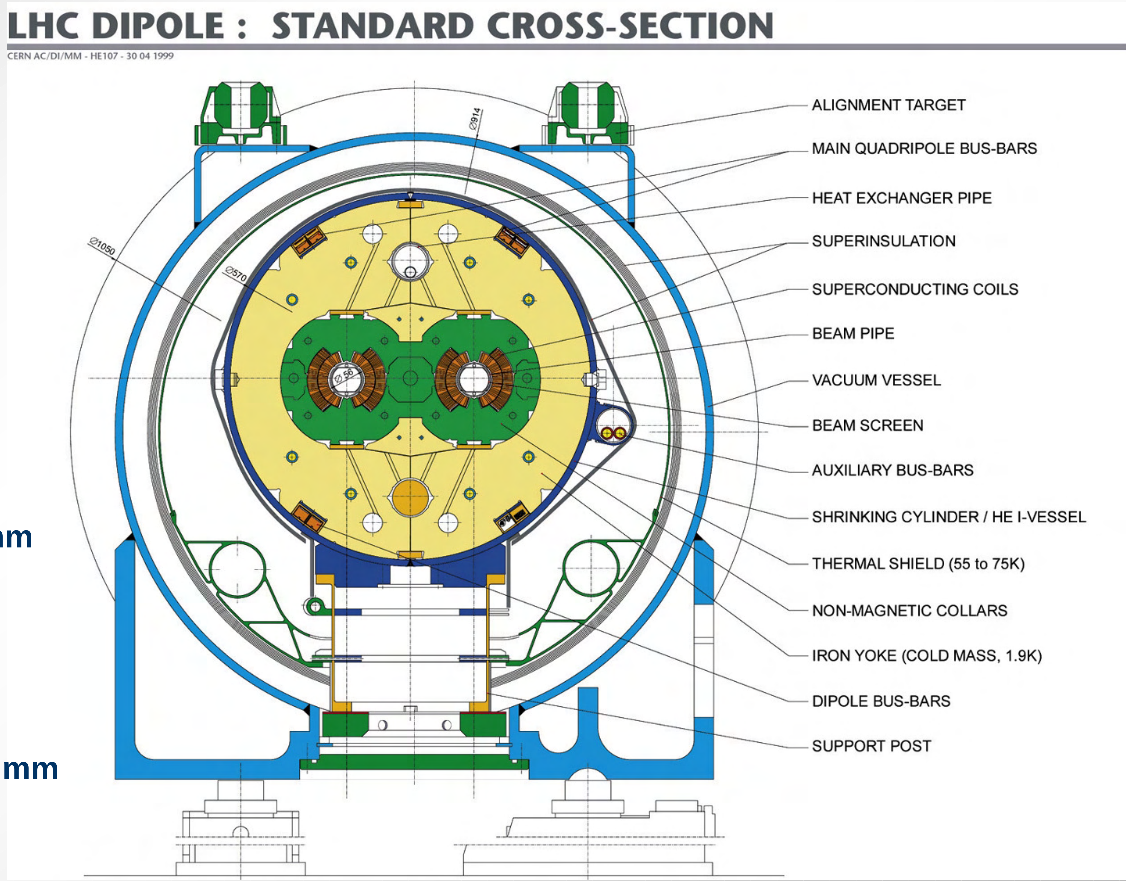
Dipole **Quadrupole** **MCS**

MCDO

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

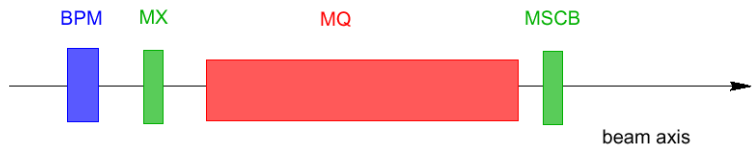


Magnets for the LHC

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

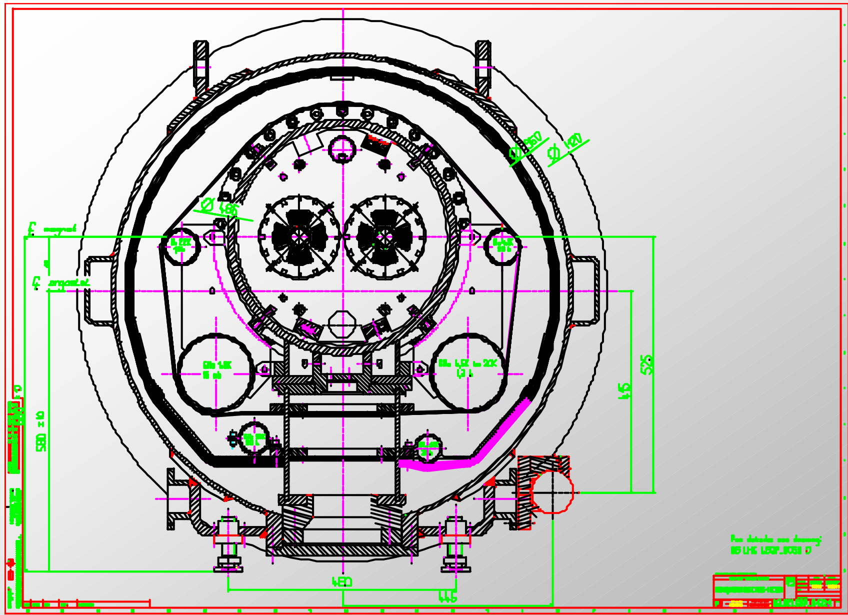
Parameter List of LHC Main Quadrupoles

Integrated gradient		690	T
Nominal temperature		1.9	K
Nominal gradient		223	T/m
Margin on load line		19.7	%
Nominal Current		11870	A
Magnetic length		3.10	m
Beam separation distance (cold)		194.0	mm
Inner coil aperture diameter (warm)		56	mm
Outer coils diameter		118.6	mm
Outer yoke diameter		452	mm
Collar material		Stainless steel	
Yoke material		Low carbon steel	
Yoke length including end plates		3250	mm
Number of turns per coil (pole)		24	
Cable length per pole		160	m
Cable length per two-in-one quadrupole		1280	m
Cable width		15.10	mm
Cable thickness, bare		1.362/1.598	mm
Insulation thickness	azimuthal, compressed	0.11	mm
(all polyimide)	radial	0.13	mm
Number of strands		36	
Diameter of strand		0.825	mm
Cable twist pitch length		100	mm
Cu/SC ratio		1.9	
Number of filaments in strands		6500	
Filament diameter		6	μm
Filament twist pitch length		25	mm
Self-inductance, one aperture		5.6	mH



MX: MQT, MQS, MO,

MSCB: orbit corrector (h and v), MS, MSS



Magnets for the LHC

Correctors

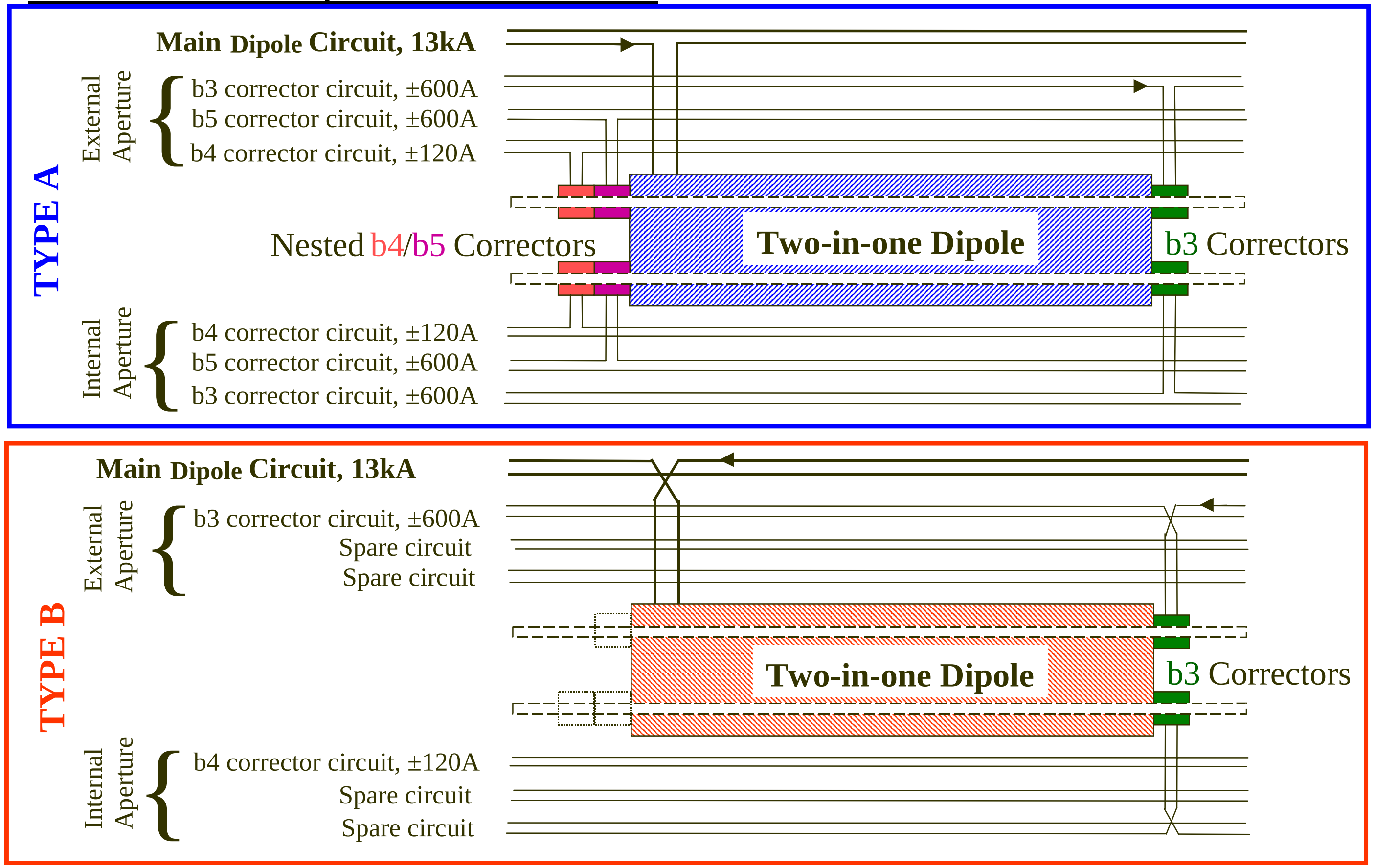
- Lattice :
  - MQTL
  - MQT
  - MQS
  - MQSX
  - MQSXA
  - MS
  - MSS
  - MO
- Orbit (H&V) :
  - MCB
  - MCBC
  - MCBR
  - MCBY
  - MSCB
  - MCBX
  - MCBXA
- Multipole :
  - MCD
  - MCO
  - MCS
  - MCOX
  - MCSX
  - MCTX
  - MCOSX
  - MCSSX

See talk by F.Patru for all the details

Magnets for the LHC

Correctors (cont)

LHC Main Dipole Correctors:



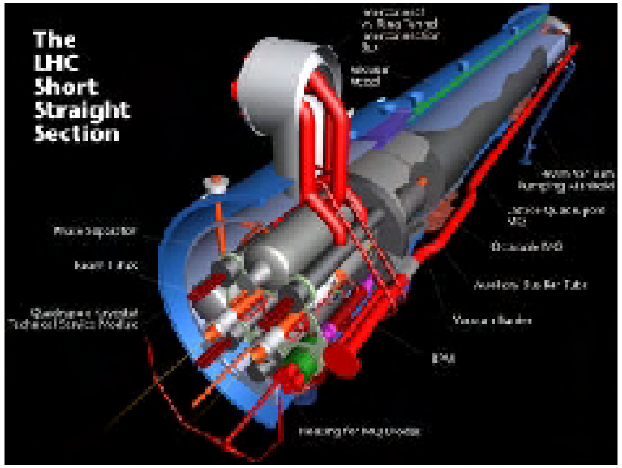
Magnets for the LHC

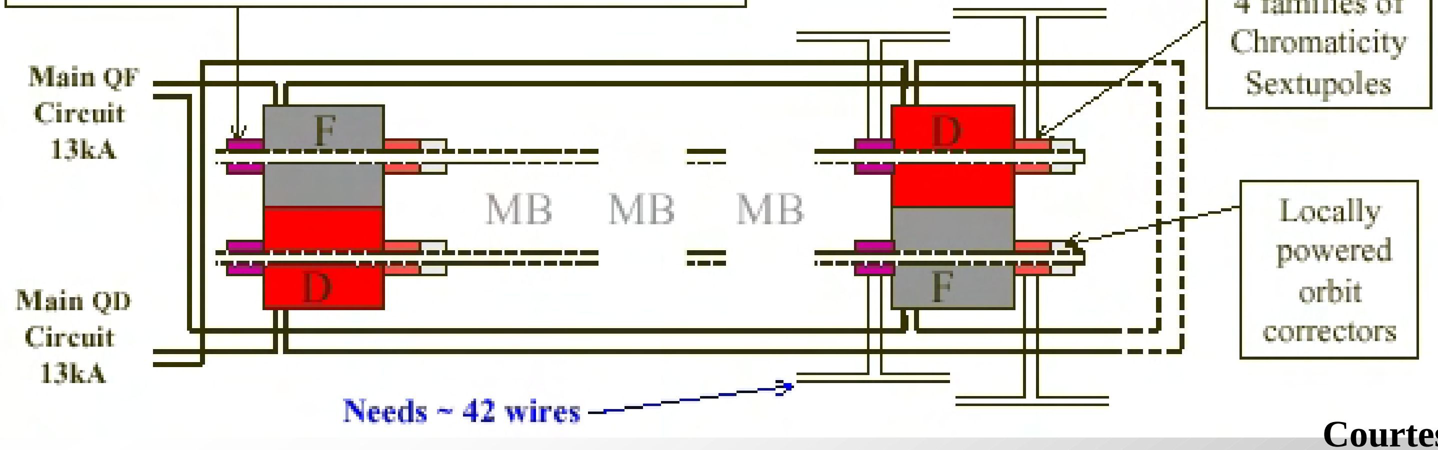
Correctors (cont)

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





Courtesy P.Proudlock

Magnets for the LHC

LHC insertion magnets

- MQM matching quadrupoles

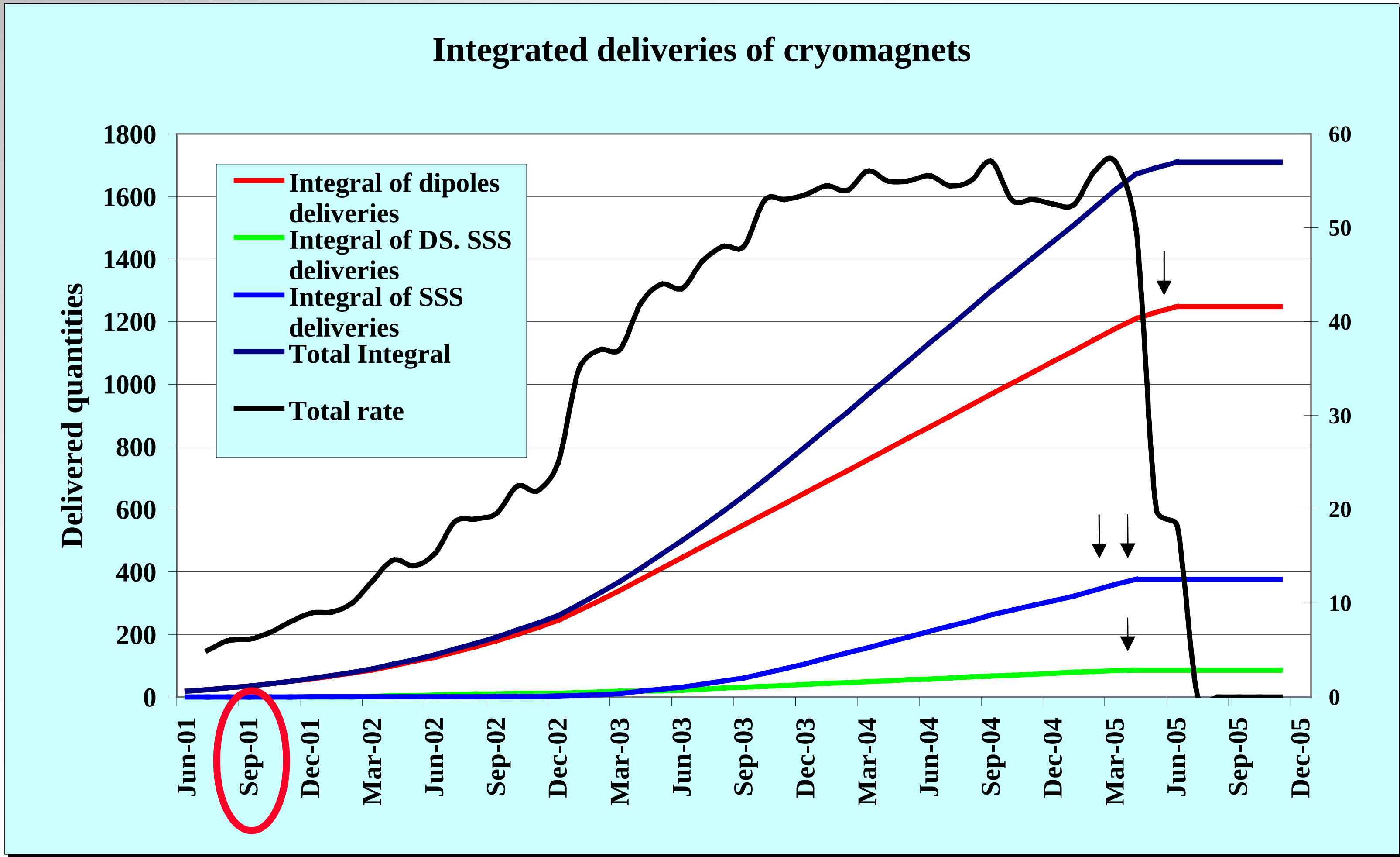
- MQY quadrupoles

- Separation dipoles (BNL)

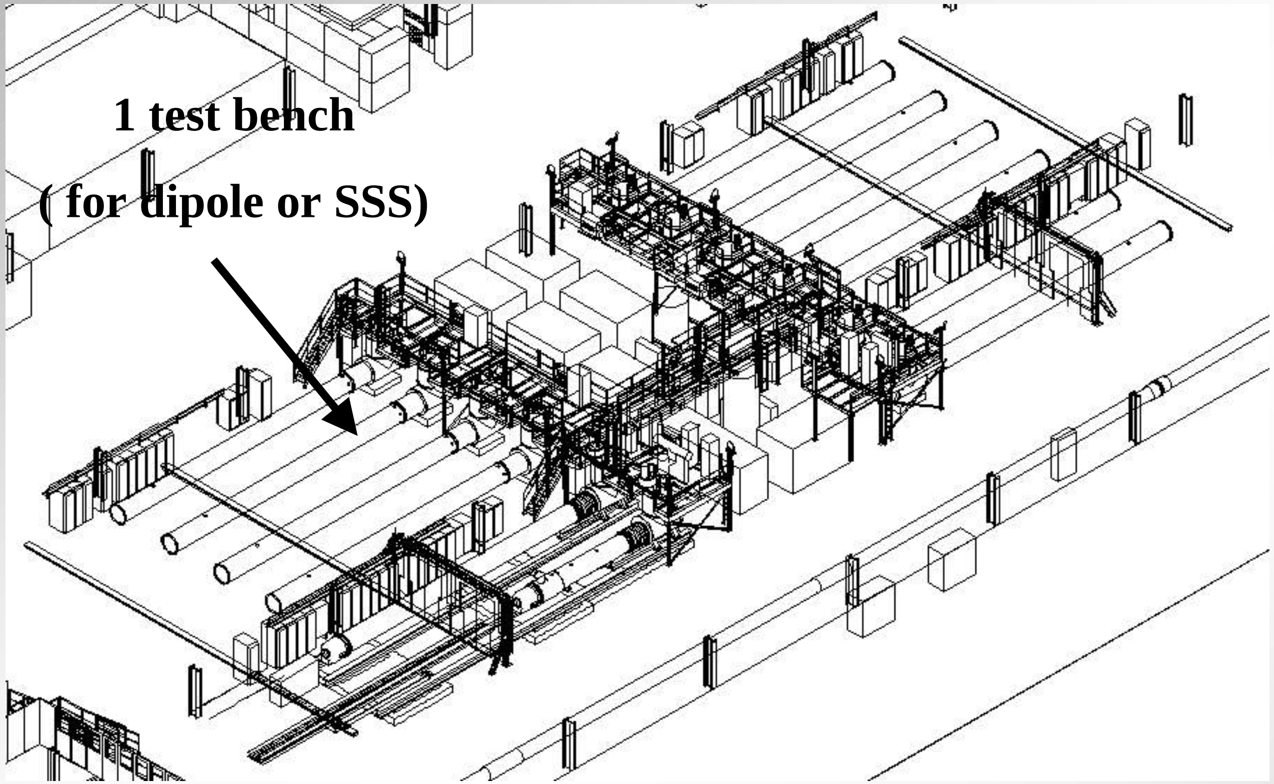
- MQXA, MQXB quadrupoles (KEK, FNAL)

Not discussed in this talk.

Dipoles and SSS to be measured.

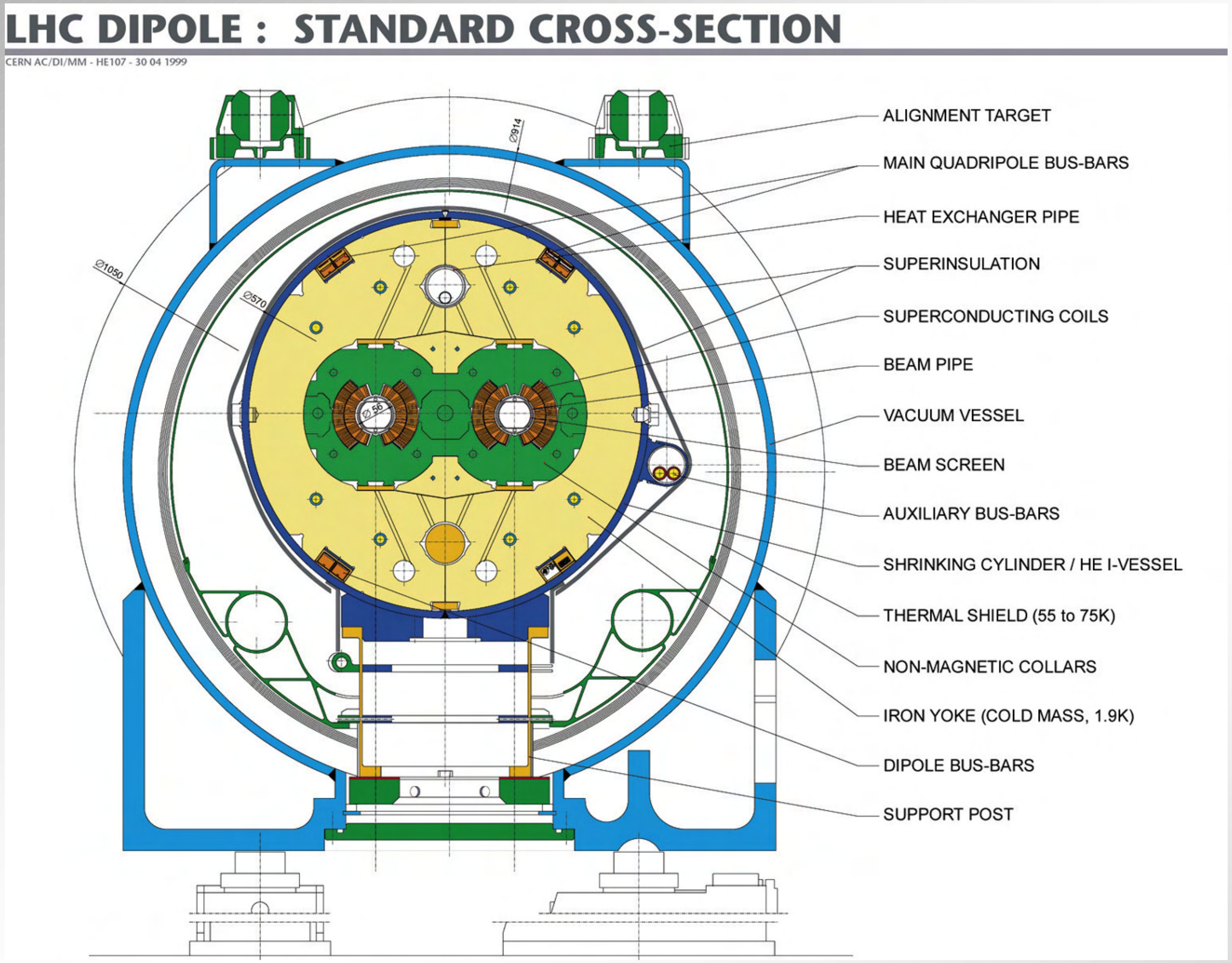


Superconducting Magnet Tests Plant (SMTP) in SM18 - 12 test benches for cold tests at CERN.



- 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



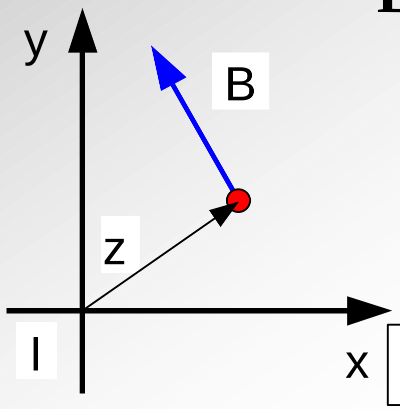
- Coil characteristics
- Collars
  - *-geometry*
  - *-magnetic properties*
- Iron yoke and inserts
  - *- geometry*
  - *- magnetic properties*
  - *-"two in one" configuration*
- Properties of the NbTi Rutherford cables.
  - *- magnetisation at 0.5 T controlled within 4.5 %.*
  - *- minimum inter strand 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**



$$\mathbf{B}_y + i\mathbf{B}_x = \sum_{n=1}^{\infty} C_n \left(\frac{z}{R_{ref}}\right)^{n-1} =$$

$$= \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{z}{R_{ref}}\right)^{n-1} =$$

$$= |C_m| \sum_{n=1}^{\infty} \frac{(b_n + ia_n)}{10^4} \left(\frac{z}{R_{ref}}\right)^{n-1}$$

Skew

Normal

Relative to main field (units)

Reference radius (17 mm for LHC)

Beam requirements

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

Effect of the field errors:

- unstable transverse particle motion (amplitude growth, larger beam size)
- aperture restrictions ⟶ beam losses ⟶ 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 $\Delta E/E << 10^{-4}$ → ***Tolerance on b_1***
- control of the orbit errors → ***Tolerance on b_1, a_1, b_2, a_2.***

Dynamical Aperture (12 σ max):

- control of the tune variation ΔQ (3.10^{-3}), the tune coupling (3.10^{-3}) and vertical dispersion.
- avoid de-tuning with amplitudes and resonances

→ ***Limits on*** ***b_2, a_2 b_4, a_4 b_5, a_5, b_7.***

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

multipole	systematic	uncertainty	random
b1	0.3	0.8	0.13
b2	0.55		
a2			0.8
b3	0.02		
a3		0.17	2.1
b4		0.07	0.49
b5	0.18		

For a series production :
Systematic = average value (gaussian distribution)
Random = standard deviation σ (gaussian distribution)
Uncertainty (in the average) = bias from the expected systematic value.

Beam requirements

Table 2 Alignment tolerance for the dipole CMA

		Tolerance systematic	random (1 σ)	Uncertainty (1 σ)
MB	x	0.14 mm	0.29 mm	0.47 mm
	y	0.14 mm	0.42 mm	0.29 mm
	roll	0.5 mrad	0.5 mrad	-
MSC	x	0.1 mm	0.34 mm	0.31 mm
	y	0.1 mm	0.61 mm	0.19 mm
	roll	1 mrad	1 mrad	1 mrad
MOC	x	31.9mm	1.9 mm	2.2 mm
	y	20.1 mm	1.6 mm	1.9 mm
	roll	1 mrad	1 mrad	1 mrad
MDC	x	0.4 mm	0.64 mm	1.3 mm
	y	1.1 mm	0.50 mm	1.7 mm
	roll	1 mrad	1 mrad	1 mrad

Table 3 Alignment tolerance for the SSS components

	Error		Tolerance systematic	random (1 σ)
MQ	orbit excursion	x	-	0.37 mm
	orbit excursion	y	-	0.37 mm
	coupling	roll	0.3 mrad	1.0 mrad
MS	tune/ß-beating	x	0.1 mm	1.0 mm
	coupling	y	0.1 mm	0.8 mm
	chromatic. coupling	roll	2.0 mrad	1.5 mrad
MO	chromaticity/ DA	x	0.16 mm	1.9 mm
	chromatic coupling	y	0.1 mm	0.5 mm
	(2,-2)resonance	roll	1.0 mrad	1.5 mrad
CB	coupling	roll	0.6 mrad	0.6 mrad

(source: W.Scandale, LHC/MMS)

Tight tolerances on alignment.

Target field quality for series production (Dipoles)

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

From S.Fartoukh and O.Bruning, LHC Report in press

Target field quality for series production (MQ)

I=12000 A

	Nominal warm, without yoke	Nominal warm, with yoke	Nominal cold	Systematic errors allowed	Random errors σ
a3				±2.0	1.0
b3				±2.0	1.0
a4				±0.5	0.7
b4				±0.5	0.7
a5				±0.5.	0.6
b5				±0.5	0.6
a6				±0.3	0.5
b6	4.16	3.93	3.97	±1.0 (1.5 cold)	0.5
a7				±0.15	0.15
b7				±0.15	0.15
a8				±0.1	0.1
b8				±0.1	0.1
a9				±0.1	0.1
b9				±0.1	0.1
a10				±0.1	0.3
b10	-0.28	-0.26	-0.27	±0.2	0.3

***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

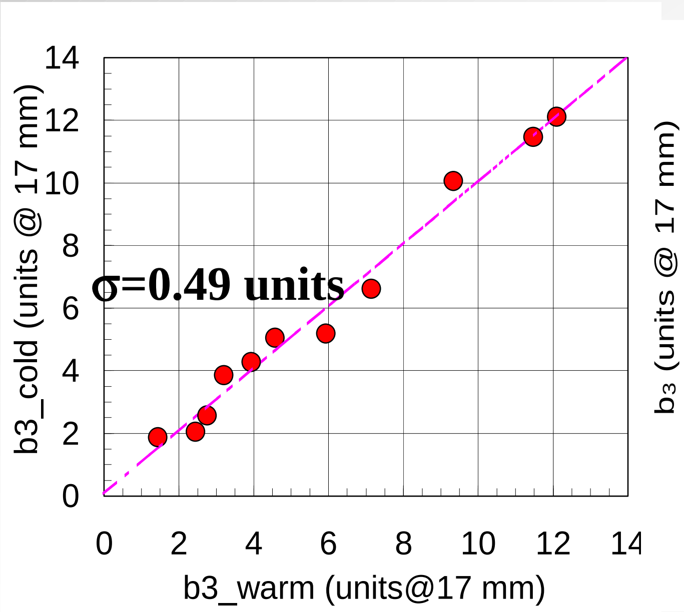
or beam induced effects can be measured and controlled !

Quality control levels and series measurement plan.

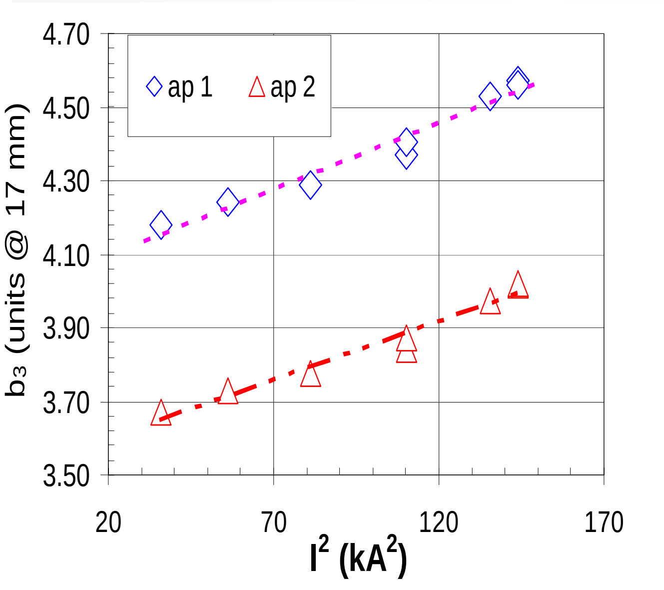
Gap between beam requirements/magnets as produced

- **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.**

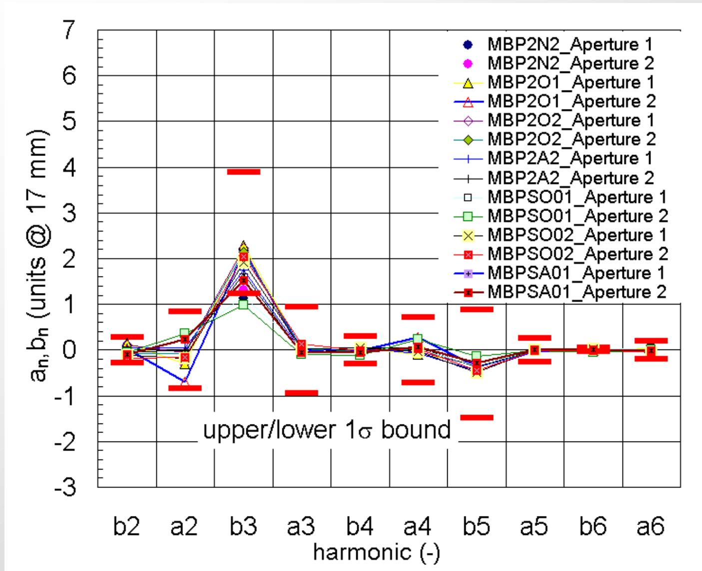
Geometric errors (warm/cold correlation)



Effect of the Lorentz Force on b_3 geometric



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



$\Delta\xi$=52 Δb_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 μΩ.**

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)

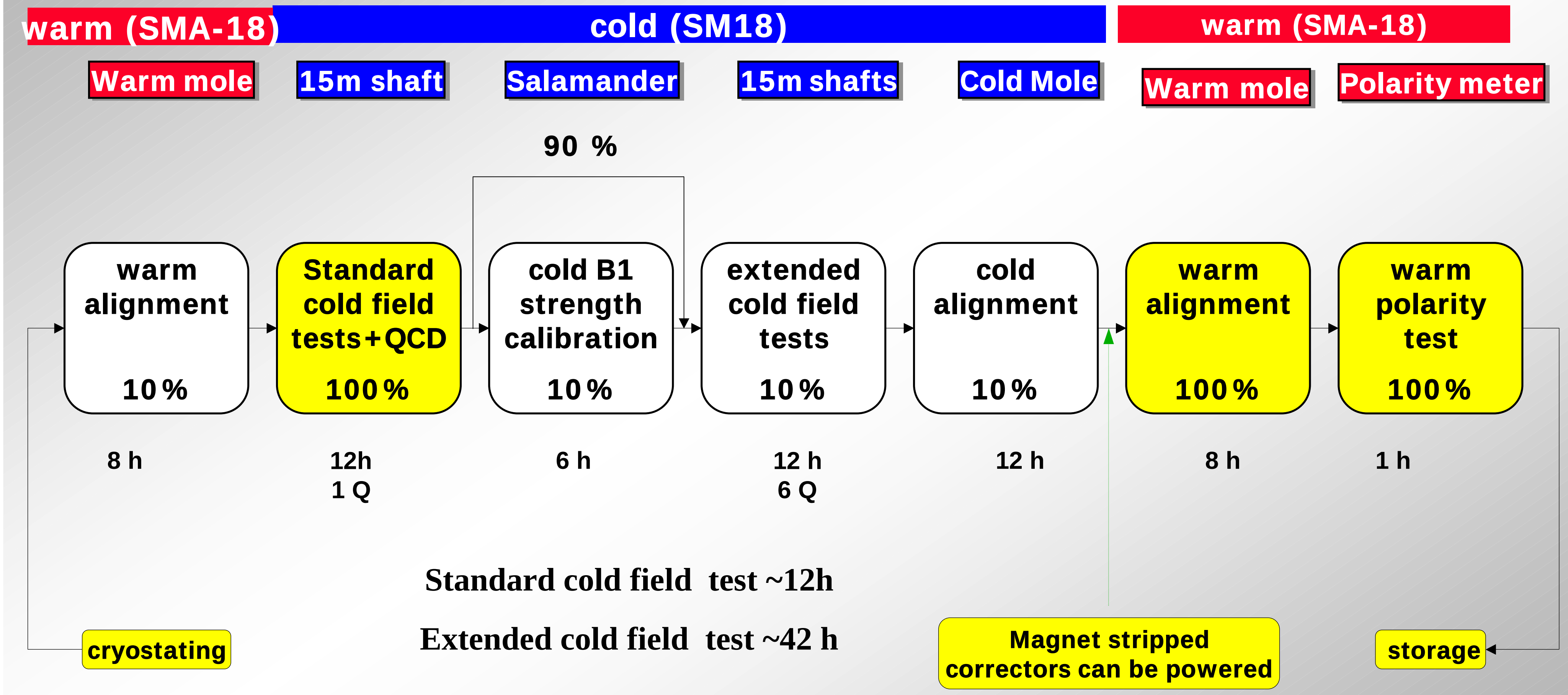
At this stage the control of the cold properties is not possible:

- deformation during cool down and under e.m. loads,

- iron saturation and superconducting cable effects.

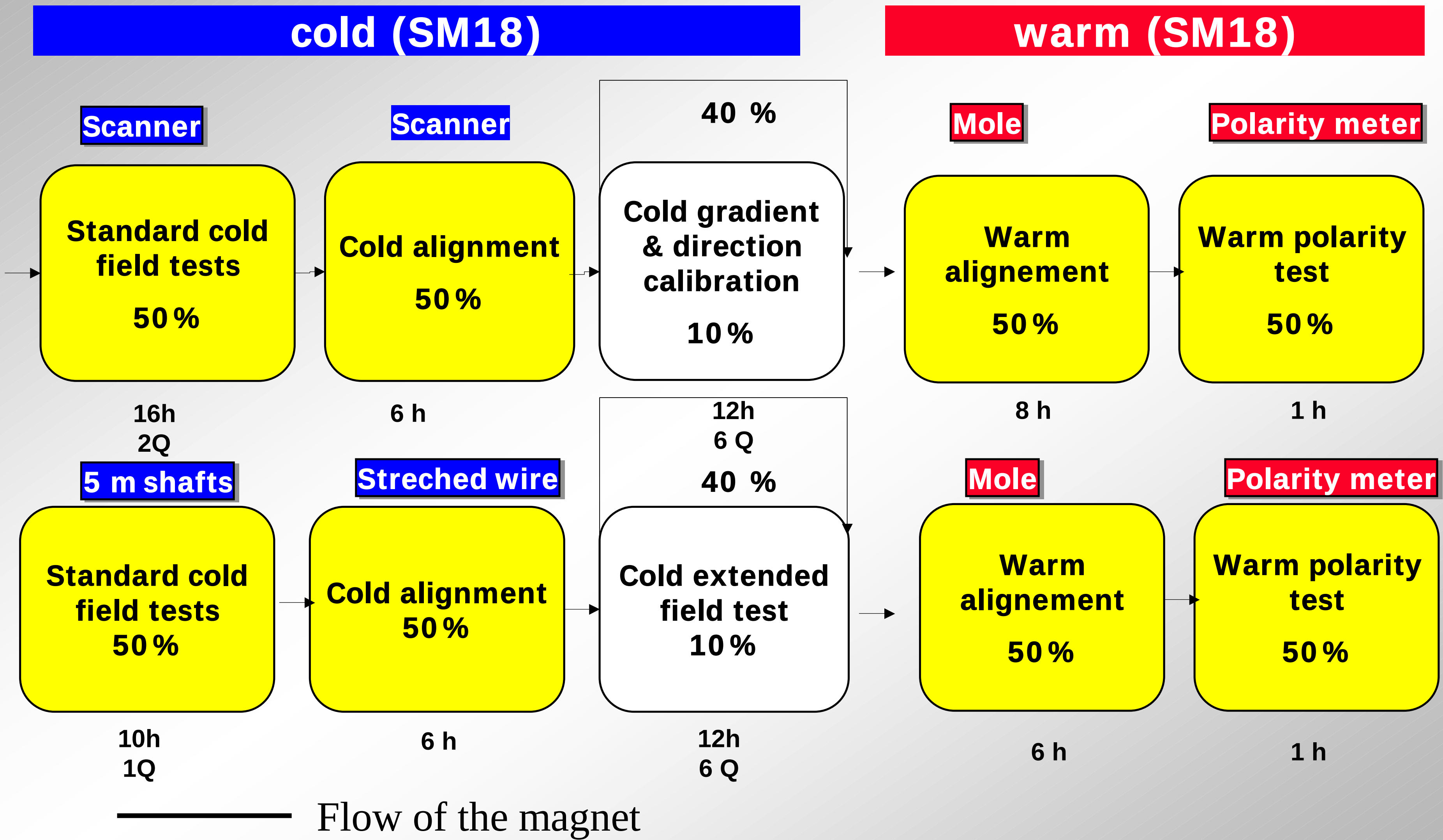
....Field quality measurements at cold are necessary!

MB SERIES MEASUREMENT PLAN AT CERN



Flow of the magnet

SSS SERIES MEASUREMENT PLAN AT CERN



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) ⇒ 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)**

(talk by M.Buzio)

- **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

		absolute	reproducibility
Main field and field integral	(-)	$1.0\ 10^{-4}$	$1.0\ 10^{-4}$
Integral transfer function	(-)	$1.0\ 10^{-4}$	$1.0\ 10^{-4}$
Main field direction with respect to fiducials	(mrad)	0.2	0.1
Harmonics	(units @ 17 mm)	0.01	0.01
Magnetic center with respect to fiducials	(mm)	0.15	0.15

Note: test durations do not include installation

Target measurements for main quadrupoles

		absolute	reproducibility
Main field and field integral	(-)	$5.0\ 10^{-4}$	$1.0\ 10^{-4}$
Integral transfer function	(-)	$5.0\ 10^{-4}$	$1.0\ 10^{-4}$
Main field direction with respect to fiducials	(mrad)	0.3	0.1
Harmonics	(units @ 17 mm)	0.05	0.01
Magnetic center with respect to fiducials	(mm)	0.15	0.15

Note: test durations do not include installation

Equipment

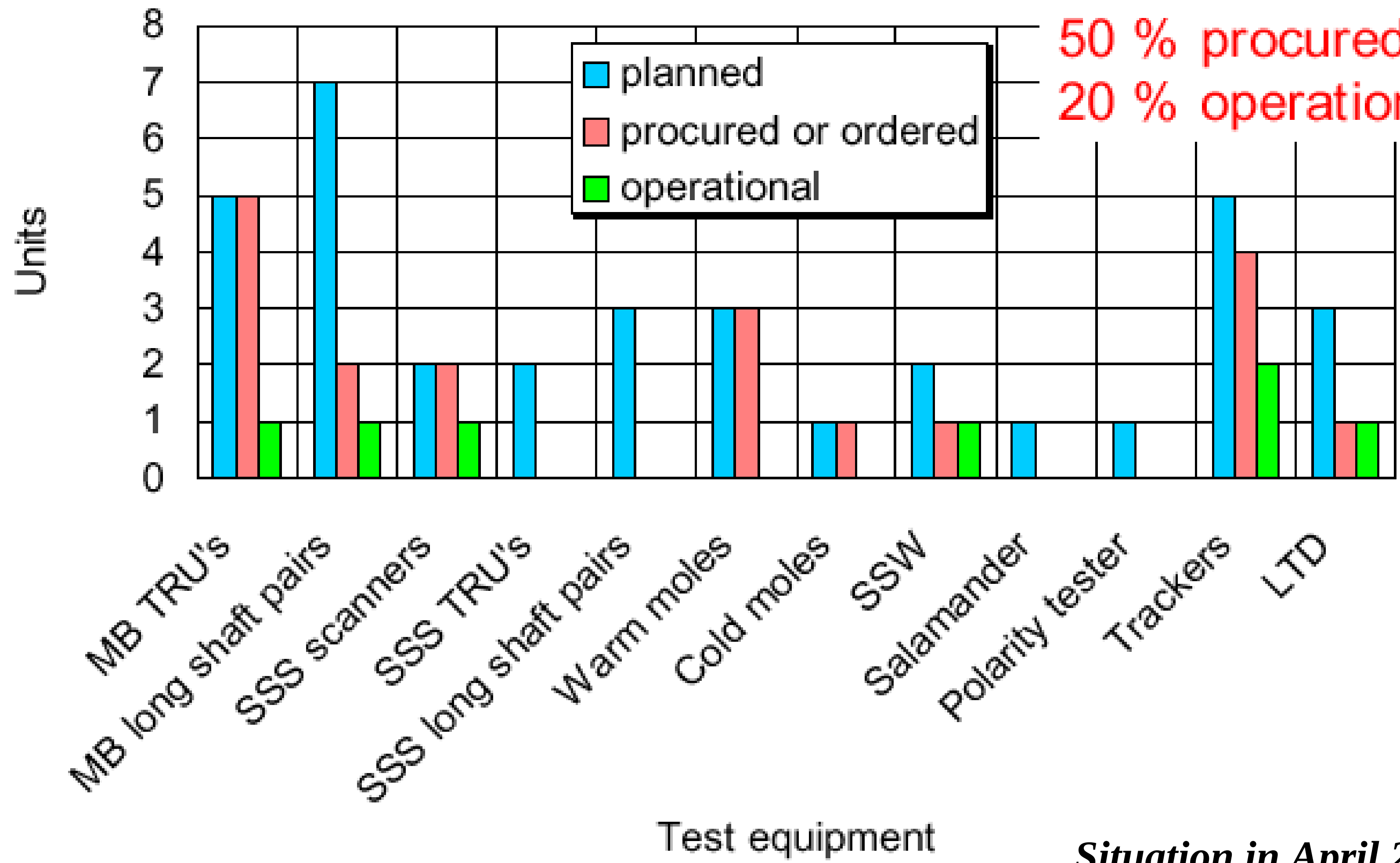
Equipment	Units planned	Procured	Aim
Twin rotating coils for main dipoles	7 shaft pairs 5 TRU's	2 coils pairs 5 TRU's	integral and local field, direction, harmonics in main dipoles
Automated scanners	2	2	integral and local field, direction, harmonics and axis in SSS
Twin rotating coils for SSS	3 shaft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

Talk by N.Smirnov

Talk of M.Buzio

In progress

Equipment



50 % procured
20 % operational

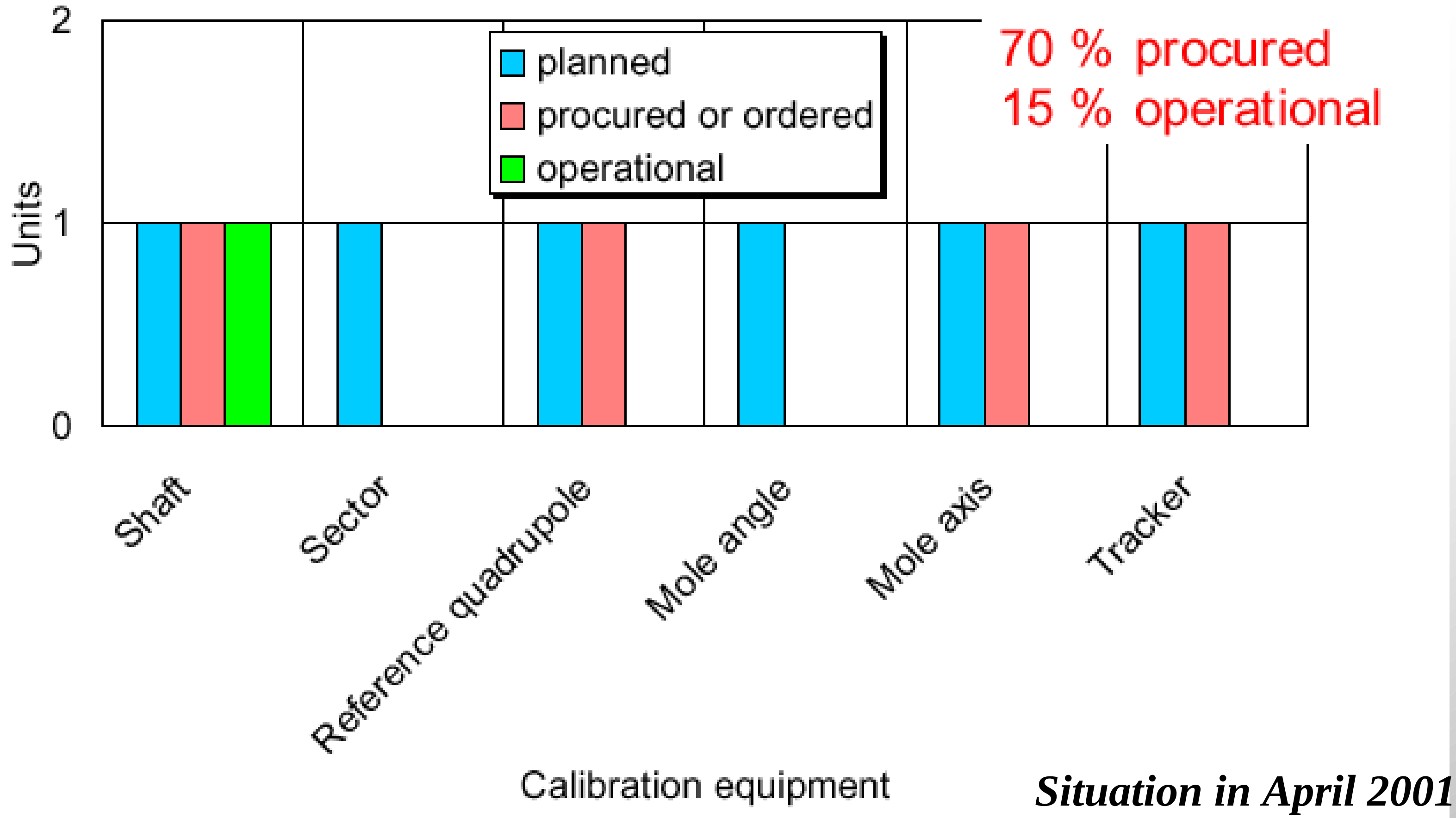
Situation in April 2001

Bench calibration equipment

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

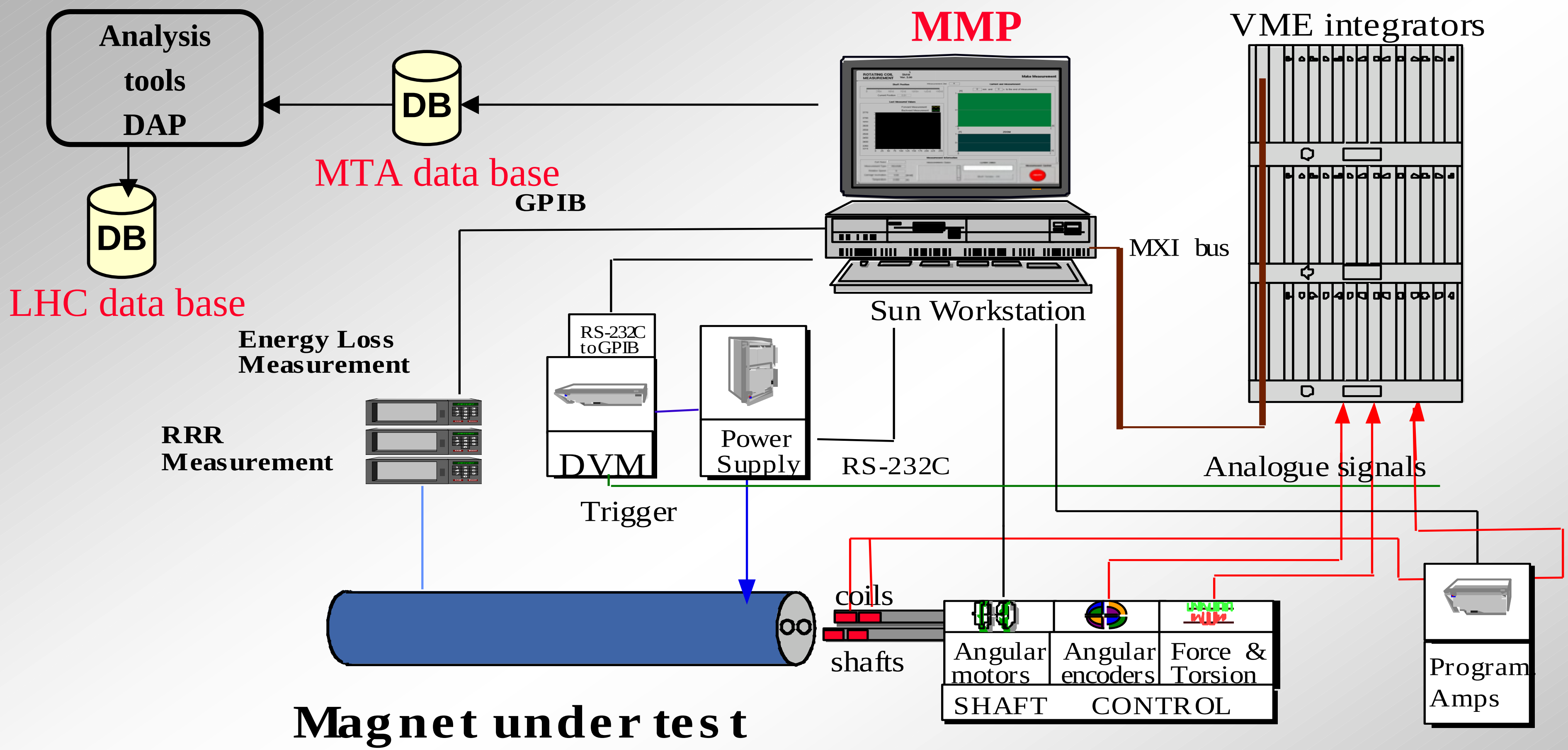
Talk of G.Deferne

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.