

Measurement and Analysis of Axial End Forces in a Full-Length Prototype of LHC Main Dipole Magnets

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Abstract — A full-length, twin aperture prototype (MBP2N1) dipole magnet for the LHC project was assembled at CERN with collared coils delivered by industry. The design of this prototype is close to that foreseen for the dipole series manufacture as far the coil geometry and that of the yoke components are concerned.

The bolts that transfer the axial magnetic forces from the coil ends to the cold mass end plates were instrumented to verify the axial coil support. These axial forces were initially measured after partial assembly, during a standard and an accelerated cool down Introduction to 1.9 K, and during magnet excitation up to 9.2 T. High force levels were observed, triggering a comparison with analytical models and measurements routinely made on 1-m single aperture dipole models. The prototype magnet was re-assembled with lower initial axial force settings and with additional instrumentation, to monitor these forces during the entire assembly process, and re-tested, to possibly correlate axial forces with training behaviour. This paper reports about the experimental observations and provides models towards their understanding.

I. INTRODUCTION

Some of the mechanical instrumentation used in the LHC dipole short model program [1], [2], [3] was introduced in a full length LHC twin-aperture prototype (MBP2N1). Companion papers at this conference [4], [5] describe its design, close to the series manufacture design.

The axial forces on the coil ends, which are retained by the magnet end plates, were measured for the first time on a dipole prototype during assembly, cool down and excitation. An initial axial pre-load (MBP2N1.V1) was chosen to ensure a correct contact between coil ends and end plates at 1.8 K. The magnet was cooled down with a standard cool down rate ("slow" cool down) and with an accelerated one ("fast" cool down). An accelerated cool down can reduce the time needed for the reception tests of the magnets and for LHC commissioning and operation. The transient thermal axial forces that can occur during such a fast cool down had to be verified.

During excitation, the increase of axial forces on the ends was measured and the distribution of axial electromagnetic forces between the magnet components was estimated. After a first test run, the magnet was reassembled with a lower axial pre-load (MBP2N1.V2), and tested again.

II. INSTRUMENTATION

Eight bolts, instrumented as axial compression load cells, apply a load between the 50-mm thick end plate and the magnet coil ends (two bolts per end and per aperture – see Fig. 1). Each load cell consists of four strain gauges in a six-wire full bridge configuration. The gauges are compensated for temperature and magnetic field, and are positioned in such a way that there is almost no influence from bending and edge effects. Each load cell is calibrated for force and temperature. The absolute error of the load cell at 1.8 K should be smaller than 10 % [6].

Appropriate strain gauges were added during the re-assembly of the magnet to monitor the strain created by the weld of the magnet end covers, the strain in the magnet end plates and the distribution of the longitudinal strain in the shrinking cylinder.

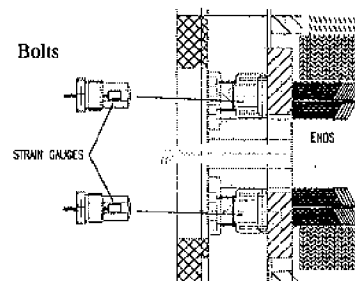


Fig.1. The bolts apply a force on the coil ends

Resistance temperature sensors measured the temperature distribution of the magnet during the thermal cycles. The temperature gauges of the cold mass were positioned on the outside of the shrinking cylinder at the two extremities and at the middle of the magnet.

III. MEASUREMENTS AND DISCUSSION OF RESULTS

A. Assembly and Re-Assembly

After partial assembly of the cold mass, the load cell bolts were tightened with a torque key, applying an axial pre-load to the coil ends. A high increase of bolt forces was observed after the welding of the magnet end covers to the cold mass. This increase was confirmed and explained with additional strain gauges during the disassembly and re-assembly of the magnet end covers for MBP2N1.V2. The shrinkage of the circular weld that attaches the end covers to the cold mass (see Fig. 2)

created a bending moment to the end plate, balanced by an increase of the bolt forces. Residual strain levels on the stainless steel shrinking cylinder in the zone between end plate and end cover weld were measured as high as 800 $\mu\text{m/m}$ and geometrical measurements indicated plastic deformation of the cylinder.

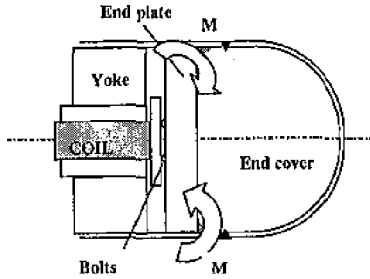


Fig.2. Bending of the end plate created by welding

TABLE I
BOLT FORCES ASSEMBLY, FORCE/END/APERTURE (A)

	Pre-load force (kN)		End covers welded (kN)	
	A1	A2	A1	A2
MBP2N1				
V1 CS	56	57	82	85
NCS	56	56	96	1)
V2 CS	11	11	18	33
NCS	10	10	43	47

Connection (CS) and Non Connection Side (NCS)

The pre-load of the bolts was lowered for the re-assembly. This resulted however in a higher spread of forces between the bolts after welding (see Table I).

B. Thermal Cycles

1) *First part of the cool down (300 K to 80 K):* During a cool down to 80 K, gaseous helium with decreasing temperature for a standard ("slow") cool down (cool down rate 1 to 0.14 K/min) and helium at 80 K for an accelerated cool down (9 K/min at CS), is injected from the connection side.

TABLE II
AXIAL END FORCES (KN/APERTURE AT 295 K AND 1.8 K FOR SLOW AND FAST COOL DOWN

MBP2N1		295 K		1.8 K	
slow	V1 CS	82		100	
	V1 NCS	95		118	
fast	V1 CS	95		117	
	V1 NCS	88		117	
slow	V2 CS	A1 16	A2 36	A1 15	A2 55
	V2 NCS	A1 41	A2 45	A1 70	A2 61

1) Not measured

A small transient increase of axial force was measured at the connection side during the start of the slow cool down. After this, the forces increased more gradually (Fig.3).

During the accelerated ("fast") cool down (9 K/min at CS) the axial forces at the connection side increased rapidly (Fig. 4) to a maximum of 190 kN/end/aperture (Fig. 4).

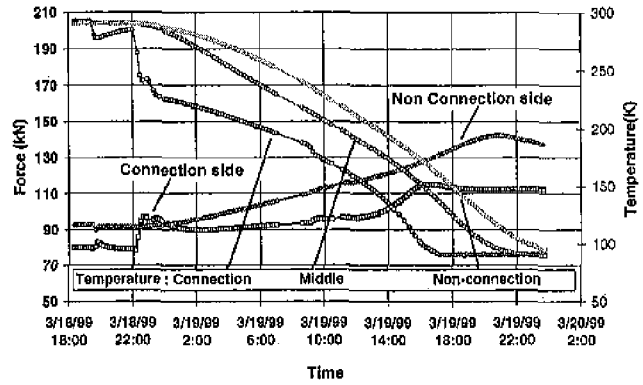


Fig.3. MBP2N1.V1 Slow cool down, force/aperture

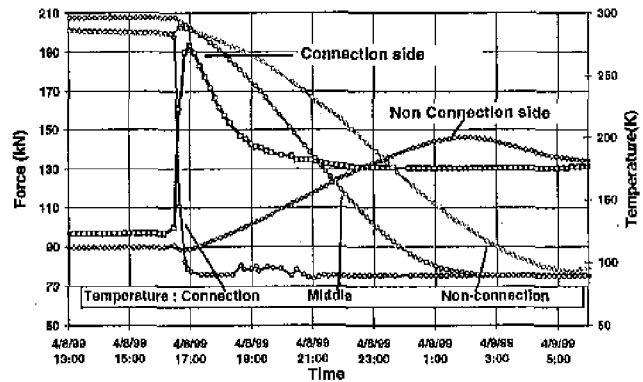


Fig.4. MBP2N1.V1 Fast cool down, force/aperture

This transient increase of bolt forces at the beginning of a cool down can be explained by high thermal gradients and thermal deformation of the connection side of the magnet, thermally shocked by the injection of cold helium. A model [7] predicted the increase of bolt forces created by local conical deformation of the shrinking cylinder and thermal deformation of the end plate (see Fig. 5).

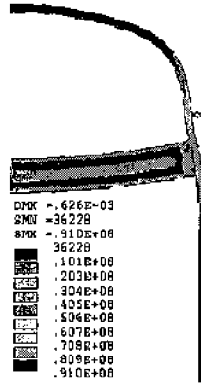


Fig.5. Transient thermal deformation of the end plate

2) *Second part of the cool down (80 K-4.2 K):* During the second part of the cool down, helium at 4.2 K is injected into the cold mass. A small initial, transient increase in bolt force was followed by a decrease of about 20 kN/aperture on both connection and non-connection side. This decrease towards the end of a cool down needs further analysis and might be related to a decrease of the mating force between the collars and the stainless steel part of the yoke laminations at the end of the cool down.

After the completed cool down, there was a net increase of bolt forces. A summary of the force values before and after cool down is given in Table II.

C. *During Powering of the Magnet*

During excitation, the load cells registered the part of the axial electromagnetic force transferred to the magnet end plate. The increase of bolt force was linear with current squared. For MBP2N1.V2, the bolt forces were not well distributed after assembly between the two apertures at the connection side. Aperture A1 transferred less force to the end plate during excitation (see Tables III and IV).

TABLE III
INCREASE OF AXIAL END FORCES IN KN/K²/APERTURE (*TYPICAL 1-METRE MODEL, 70 MM END PLATE, 6-BLOCK COIL)

MBP2N1.V1		MBP2N1.V2		1-metre model *	
CS	NCS	CS	NCS	CS	NCS
0.64	0.67	0.09 (A1)	0.62	0.36	0.42
		0.63 (A2)			

TABLE IV
ABSOLUTE AXIAL END FORCES REACHED AT NOMINAL FIELD (KN/APERTURE)

MBP2N1 V1		MBP2N1 V2		1-metre model *	
CS	NCS	CS	NCS	CS	NCS
198	207	25 (A1)	155	60-90	60-90
		150 (A2)			

The axial strain in the shrinking cylinder was measured with eight strain gauges distributed over half of the length of MBP2N1.V2 (see Fig. 8).

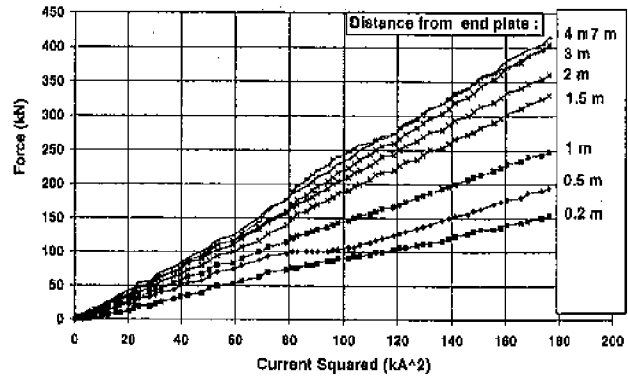


Fig.6. Axial strain in the shrinking cylinder

The axial electromagnetic forces will create an elongation of the coil that is retained by the bolts and by the friction between the coils, collar and yoke laminations. From the measurements it shows that the part of the electromagnetic force that is transferred to the shrinking cylinder develops over the first two metres from the ends. The measured strain at the middle of the magnet corresponds to about 93% of the axial electromagnetic forces being supported by the shrinking cylinder and 7% by the coil and other structures like collaring rods (for 375 kN electromagnetic force calculated at nominal field [8]). The mentioned force in the cylinder was however calculated by considering the axial rigidity of the shrinking cylinder only. The combined stiffness of cylinder and yoke laminations may be higher.

D. *Evolution of the End Forces*

The axial end forces per aperture of MBP2N1.V1 at different moments during the testing are shown in figure 7. The increase of 25-35 kN per aperture after the welding of the end covers is shown again. There was a net increase of the bolt forces of 20 kN per aperture after a standard cool down and 30 kN per aperture at the connection side after an accelerated cool down.

The forces measured at zero current were quite stable during the current cycles and throughout the first 14 quenches. They increased 9 kN/aperture at the connection side and 7 kN/aperture at the non-connection side. There was hence some ratcheting (or build up of axial pre-load).

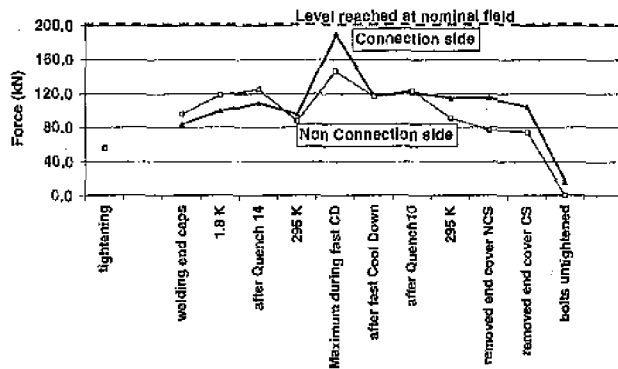


Fig.7. Variation of bolt forces at different stages (kN/aperture)

After the first warm-up, the forces reached the same level as before the first cool down. However, after the accelerated cool down, the forces at the connection side increased by 9 kN/aperture. After the second warm-up, the forces at the connection side were higher than before the first cool down. This indicates that some irreversible movements took place during the accelerated cool down.

The welds that attached the magnet end covers to the magnet cold mass were cut during the magnet disassembly.

The elastic part of the conical deformation of the shrinking cylinder was released during this operation and the axial forces on the coil ends were reduced by 14 kN/aperture at the connection- and 11 kN/aperture at the non-connection side. A part of the conical deformation was found to be permanent. The measurement of the untightened bolts revealed that some of the bolts at the connection side had a small zero offset because of plastification. The instrumentation was not foreseen for the very high forces reached during the accelerated cool down.

The influence of the axial end forces on the training behaviour is not yet clear. All quenches but two were in the coil ends, most likely however because of a lack of azimuthal pre-stress in the coil ends [5]. The level of end forces reached was much higher than that of the forces usually measured in 1-m single aperture dipole models. Some short models were tested with higher initial axial pre-load, but there was no clear effect on the training behaviour [9].

Before the fast cool down, all training quenches were at the non-connection side. After the accelerated cool down, training quenches moved to the connection side end, the side where the helium is injected and where the high transient thermal forces were measured. More testing and analysis is needed to confirm the observed behaviour.

The training behaviour of MBP2N1.V2, reassembled with a reduced axial pre-load (see Table I), was not very different from that observed for MBP2N1.V1. Because of the lower initial values, the bolt forces reached at nominal field were however 25 % lower. More tests are needed to confirm any

influence of the force level at the axial bolts on magnet training.

IV. CONCLUSIONS

The mechanical measurements introduced in the full-length LHC twin-aperture prototype (MBP2N1) dipole magnet were found to be very useful. The load cells on the end bolts have shown a significant increase of axial force on the coil ends after the welding of the magnet end covers. A net increase of bolt forces was also measured after cool down. The initial axial pre-load was lowered during a subsequent re-assembly, still guaranteeing a good axial coil support at 1.8 K.

The measurements made during excitation and from quench to quench gave more information about the participation of the different magnet components in retaining the axial electromagnetic forces. The axial electromagnetic forces are almost completely transferred, over the first 2 m from the magnet ends, to the shrinking cylinder. The end bolts transfer about 45 % of the load to the end plates and from there to the shrinking cylinder. The remaining 55 % appear to be taken by friction between coils, collars and yoke laminations.

The influence on the magnet training behaviour of the transient thermal end forces during an accelerated cool down is not clear. More tests have to be performed and the next prototypes will again be equipped with axial load cells.

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