EXPERIENCES WITH THE MANUFACTURING, TESTING AND QUALITY CONTROL OF LARGE NUMBER OF SUPERCONDUCTING MAGNETS

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Abstract

Raja Ramanna Centre for Advanced Technology has successfully completed the supply of nearly 1800 nos. Superconducting Corrector (SC) Magnets for the LHC project at CERN. Under the DAE-CERN collaboration agreement India through RRCAT, Indore was entrusted to manufacture, test & supply half of the total Sextupole Corrector (MCS) 1232 nos. and Decapole Octupole Corrector (MCDO) 616 nos. required for the LHC main dipole, while rest half were made in Europe. In this paper we describe the experience gained during technology development, prototyping and technology transfer to industry.

INTRODUCTION

The MCS & MCDO spool correctors consists of a coil assembly, glass fibre slit tube, steel laminations & aluminium shrinking cylinder for pre compression of coils, end plates for coil connection, parallel resistor for magnet protection (in case of MCS) and a magnetic shield also acting as a support. The coils have been wound using CERN supplied Nb-Ti SC wire in copper matrix.

Table 1: Main parameters of spool correctors

Parameters	MCS	MCD	MCO
Nominal strength	1970 T/m^2	1.2 X 10^6 T/m^4	8200 T/m^3
Length (mm)	160	110	
Aperture (mm)	58	63.6	58
Nom. current (A)	550	550	100
Working temp. (K)	1.9		
Turns per coil	2 x 13	2 x 20	1 x 43
Self ind. (mH)	0.8	0.4	
Quench current at 1.9K/4.2K (A)	1300/950	1250/915	297/195
Peak field (T)	1.9	2.4	2
Mass (Kg.)	~5.5	~5.0	

These corrector magnets require precision components and coils, accurate assembly procedure, elaborate testing plan and stringent quality control required for repeatable performance.

DEVELOPMENT CYCLE

Looking to the complexities and total quantum of work a two-fold strategy was adopted. All the technology was developed in-house at RRCAT in collaboration with CERN. The same was proved by way of making prototypes and elaborately testing them at 4.2 K at RRCAT & further at 1.9 K at CERN. Their large-scale production was planned at industries to make use of their infrastructure, expertise and efficiency under strict quality control from RRCAT.

Prototype Development

Prototype phase comprised of development of various critical components, tooling, coil winding & magnet assembly process and manual coil-winding machine. The coil former was CNC machined out of G-11 tubes. AISI M-45 grades Si steel laminations were punched using 0.5 mm thick sheet. Shrinking cylinder, its anodising treatment and different precision tooling for coil winding, magnet assembly & shrink fit tooling were developed at fabrication facility of RRCAT. Special bandage tooling was also developed for the application of B-stage semi cured glass epoxy tape over coil assembly, which was a messy affair. There were some troubles during assembly of hot shrinking cylinder over stacked laminations as it was getting stuck halfway. The inter coil connections were made using standard soldering. The individual modules were tested at 4.2 K in existing ϕ 200 mm bore cryostat & warm magnetic measurement (WMM) at 300 K was done at RRCAT on specially developed rotating coil vertical shaft bench. The 1.8 K training & also field quality test on these prototypes were done at CERN. The acceptance of prototype proved the tooling & process and gave confidence to proceed further [1].

Figure 1: MCS fitted at one end of LHC Dipole.

Various Developments

The zero period due to design modifications was utilised in development of components & special machine requiring long development cycle time. Compression moulding for the Central island & end spacers were tried. The dimensional accuracies were achieved however the strength was not consistent due to variation in resin and glass content from batch to batch. Different concepts were tried for automatic coil winding machine and finally cam guided twin arm type design fitted with torque motors was adopted. Similarly for low contact resistance & high productivity a 20 KHz, 4.5 kW ultrasonic welding machine was developed with the support of industries [2].

Large-scale Manufacturing

There was no industry, which had expertise & earlier experience of making SC magnet within the country. Market survey was conducted to explore the prospective manufacturer. Electrical motors manufacturer with ISO-9000 certification capable of handling large volume were pre requisite criteria.

Accordingly M/s Kirloskar Electric Co. Ltd, Bangalore was awarded order for making MCS magnet. Pre-series phase was introduced, during which the necessary technology was transferred for complete manufacturing cycle including tooling development & training personnel for various critical processes. Experience was also shared for the manufacturing of critical components with the vendors. The industrial partners were trained to adopt tolerances from tenth to hundredth of mm. As part of strategy the order for MCDO was awarded to another industry M/s Crompton Greaves, Bhopal, even though this required duplication of all infrastructure like clean room, special machine and imparting training etc.

Figure 2: Magnet production facility at Industry.

Process Modifications

Based on the experience of prototype certain modifications were also carried during series manufacturing. The semi cured 'B'-stage fibreglass tape was replaced by pre machined slit tube of G-11. Alternate use of open end & cross end coils with introduction of ultrasonic welding not only simplified the interconnections of coils but also resulted in very low contact resistance. Introduction of checking the lamination stack with a simulated hot dummy cylinder eased out the shrink fitting process to a very large extent. Initially the coil curing was tried by resistive heating by passing current through the coil itself however it was felt safe to cure the coil in the oven to avoid the risk of over burning of coil. The material of shrinking cylinder as per original specifications given by CERN was AA5082/5086 for its good mechanical strength. This material in the desired tube form was neither available nor the quantity was attractive to the manufacturer. As an alternate AA 6061 was introduced which has very good extrudability & the desired strength was achieved with temper T6. A marginal higher average compressive stresses (60-80 MPa) were maintained over the coil assembly, which resulted in excellent cold testing performance. Critical dowel holes were given suitable allowances for Electroless Nickel plating and assembly drilling were adopted for achieving tolerances of 0.01 mm. There was additional requirement of 516 MCO insert from CERN. Since the same was not agreed by the manufacturer to take up, they were made in-house at RRCAT through works contract, thanks to the infrastructure & expertise generated during prototype phase.

Figure 3: Magnets under preparation for cold testing.

TESTING & QUALITY CONTROL

Testing & quality control of nearly 2000 SC magnets being manufactured at different geographical locations nearly 1500 km away spreading over the duration of two to three years was a massive task.

Inspection and Quality Control at Industry

In pre-series magnets (a batch of ten) 100 % inspection was done. This was to prove the manufacturing cycle consisting of components & process. The philosophy of inspection during series manufacturing was based on sampling for batch control still keeping 100% inspection for identified critical parameters. Suitable gauges were employed for this. Trend monitoring was employed to keep the process within acceptable limits. The higher value of contact resistance in few lots was traced to worn out sonotrode, which was suitably repaired back. Periodic pre-despatch inspections were carried out at respective industries before despatch of each batch to RRCAT for dimensional control & electrical parameters. Magnetic measurement at warm for each magnet was also carried out on CERN built industrial magnetic measurement bench posted with each industry.

Inspection and Quality Control at RRCAT

All the SC magnets were also tested at 4.2K liquid He temperature. Since this required use of LHe and skilled manpower to handle cryogenic fluids, the cryogenic test facility was established at RRCAT [3]. The cold test plan for every magnet include training, measurement of contact resistance and ground insulation and retraining (after a thermal cycle to room temp) at 4.2 K. Starting with the capacity of testing 24 magnets per month and providing required training to the personnel the testing capacity was enhanced based on experience finally to more then 100 magnets per months to meet the schedule. Innovative technique of testing many magnets in 'series' using common current leads were also introduced for improvement of productivity & efficiency of testing with the help of sc switches specially designed & fabricated for this. Automated operation for powering & recording data using Desy-Lab based acquisition system were adopted. After the cold testing WMM was done on CERN built industrial test bench again to check for a possible variation change due to cold shock.

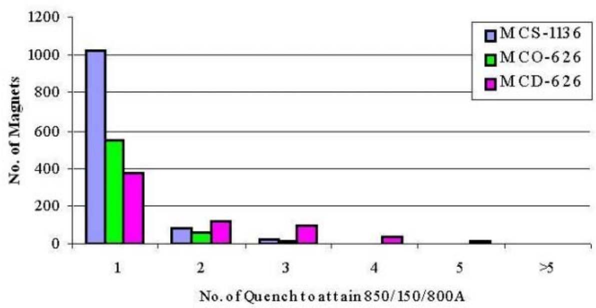

Figure 4: Training Performance of Corrector.

Table 2: Acceptance criteria for WMM & cold testing

	MCS	MCD	MCO
Axis Shift (mm) dX-dY *	0.1	0.1	0.1
Axis Shift (mm) dX-dY **	0.3	0.3	0.3
Mean & SD of Axis Shift lot of 50 (mm) dX-dY **	0.1	0.1	0.3
Axis twist (m-rad) dT *	1.5	2.5	3
Axis twist (m-rad) dT **	3	4	4
dB/B (%) mag. to mag.	<1	<1	<1
$I_{leakage}$ (300K) (µA)	<3	<3	<3
$I_{leakage}$ (4.2K) (µA)	<6	<6	<6
1 st Quench current (A)	550		100
In max 5 quench magnet to reach (A)	850	800	150
Contact resistance (nΩ)	< 35	<40	<50
No retraining Quench allowed below (A)	850	800	150

TEST RESULTS

All the magnets showed excellent cold testing result with more then 80 % reaching critical current in 1st quench itself and almost all reaching desired current with allowed 5 quenches (Fig-4). The rejection in cold testing was less then 0.5 %. For field quality at warm the main field variation was within ± 1 % (Fig-5). The limits set for axis shift & twist even though could be met during pre-series, were proving to be difficult & expensive to maintain during large series production on account of very tight tolerances (*-table-2). As the compensating errors average out & does not affect the machine performance a revised norms by keeping average & standard deviation still within original limits for a lot of 50 magnets allowing individual limits to higher values (**- table-2) was introduced. This reduced the rejection of magnets, which would not have affected the machine performance. Contact resistance was also successfully measured & was within limits with rejection below 1 %.

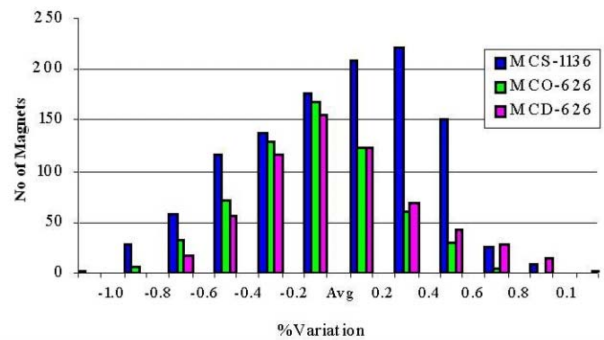

Figure 5: Main Field Variation of Corrector Magnets.

CONCLUSION

The complete project was accomplished with success with methodical planning, pre qualification by intensive testing and close monitoring on well-defined quality assurance plan. Splitting the order between Indian & Europe for each half quantity proved to be very wise. The short supply of Indian MCS magnet and long delayed supply of European MCDO magnets were compensated by their respective counterpart.

ACKNOWLEDGEMENT

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