

Preliminary Testing of Coils for the Superconducting Toroidal Magnet for the CEBAF Large Acceptance Spectrometer (CLAS)

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Abstract

The design of the six coil superconducting toroidal magnet, which is to be installed at CEBAF, Virginia, was reported by Oxford Instruments and CEBAF at the Applied Superconductivity Conference in Chicago in 1992. This paper outlines the progress being made in the manufacture and describes the testing at Oxford Instruments of some of the first coils produced. Individual coils are being tested to full current rating which generates a field of 2.8 T; this is just below the peak field in the six coil array (3.5 T). The auxiliary systems - the service module, the power supply, and the control and instrumentation system - will also be fully tested before shipment and progress with these components is also discussed.

1. SUMMARY OF SYSTEM DESIGN

A modular coil system has been developed which facilitates site assembly and allows for works testing of single coils. The coil design features an aluminium stabilised conductor which is indirectly cooled by force-flow, supercritical helium [1]. The aluminium stabiliser enhances the stability of the coil through its high thermal conductivity and low resistivity. Also its thermal contraction closely matches that of the aluminium alloy coil case. The superconducting insert cable is a fully transposed roebel bar (Rutherford cable) of nine wires of 0.95 mm diameter with 90 micron filaments.

The coils are formed by winding the insulated conductor into a CNC machined recess in the coil case. The coil case is manufactured from a single piece of forged 6061-T6 aluminium plate. Once the coil has been wound, a cover plate is fitted to the case and the whole coil is vacuum impregnated with resin. The coils are indirectly cooled and maintained at 4.5 K by a hollow cooling channel located on the inside edge of the windings. The channel carries a 5 g/s flow of supercritical helium at 2.8 ata.

The magnetic in-plane forces of 140 Tonnes on each coil are transmitted to the vacuum case at room temperature by three tension supports. These supports are manufactured from 316LN-ESR cold-worked stainless steel. The out-of-plane forces on each coil are taken by six pairs of short epoxy-glass compression struts between the coil case and its vacuum case.

Each vacuum case is in two parts with a bolted O-ring joint close to the mid-plane; each half is machined from

AISI 304L stainless steel plates initially 112 mm or 80 mm thick. The finished thickness is 15 mm over most of the area of the vacuum case. This method of construction was needed to meet the strict limits on dimensional accuracy required by CEBAF.

2. CONTROL AND INSTRUMENTATION

For data acquisition and control, CEBAF uses a proprietary system called Thaumaturgic Automated Control Logic (TACL). It runs on networked HP 9000s, and uses a CAMAC hardware interface. The magnet instrumentation is integrated into TACL.

Of more than 200 sensors on the magnet, most measure force and temperature on the coils. The signals are pre-processed on a set of Eurocards, exchanged where necessary across the backplane, to sort them into groups, and passed on to CAMAC modules. Non linear processing is done by TACL software. TACL also runs the control loops, and outputs go to the Service Module.

There is a back-up system, implemented in hardware, to protect the magnet if the TACL control system fails. It monitors key variables to ensure that there is sufficient cooling, and runs down the magnet power supply if any go out of limits.

3. RESULTS OF WORKS TESTS ON SINGLE COILS

An extensive works test programme has been followed during the manufacture and final assembly at Oxford of the individual coils. Although testing single coils does not generate the high electromagnetic forces which occur in the six-coil system, it is nevertheless a useful test to check for superconducting performance, cryogenic loads, vacuum integrity and to obtain operating experience with the control and instrumentation system, and the power supply. In principle, it would have been possible to test the six-coil system at Oxford prior to shipment but it was agreed that this would have added considerably to the delivery time and contract price and was therefore not included.

To date, four coils have been fully tested and accepted by CEBAF, and the power supply has been proven. Coils 5 and 6 and the Service Module which controls the cryogenic system will be tested during 1994. This report concerns only these four coils. Figure 1 shows the first coil on test at Oxford.



Figure 1 Works Testing the First Coil at Oxford

Magnetic Field and Electrical Tests

Four coils have now been successfully tested at Oxford with only one training quench. Three of the coils went straight to field without training quenches and the fourth coil quenched once at 85% of its operating current before, on its next energisation, achieving field. Test results from deliberately initiated quenches have correlated well with predictions with a decay time constant of ≈ 12.5 s. The peak temperature is expected to be 80 K.

Each coil has had limited field measurements made to ascertain the position of the coil within the vacuum case. These have shown that all the coils are the correct shape and are positioned centrally in the vacuum cases, in both the in and out-of-plane directions, to within 1.3 mm.

Insulation voltage breakdown tests to ground on the coils have been performed at 500 V and all have shown very high resistances between 10 G Ω and 200 G Ω .

Cryogenic Loads

The cryogenic loads, exclusive of the current leads, were measured by providing a steady flow of cold helium or nitrogen gas and measuring the temperature rise in the gas and monitoring the general temperature rise in the coil or the radiation screen over a period of time.

Table 1
Head Loads

	Heat Load at 4 K (W)	Heat Load at 80 K (W)
Coil 1	3.7	< 30
Coil 2	7.9	≈ 55
Coil 3	5.8	≈ 45
Coil 4	5.0	≈ 30

Although there is some variability from coil to coil, the 4 K heat loads are well within the budgeted figure of 10 W per coil and even after allowing for the additional cryogenic components give some confidence that the guaranteed head load of 110 W for the complete system will be satisfied.

The 80 K heat load is well below the budgeted figure and is very acceptable

The current leads used for the works tests are similar to those which will be used in the complete Torus and the temperature profile and mass flow rate when carrying the full current of 3860 A were as expected.

Mechanical Tolerances

The design, machining and assembly procedures for the vacuum cases were dictated by the strict limits on the flatness and the space which could be occupied by the vacuum case. During assembly, each half of each case was restrained to a flat condition and after bolting and raising to a vertical plane, the un-restrained vacuum cases showed out-of-flatness measurements as given in Table 2 below.

Table 2
Out-of-Flatness Results

Reference	Flatness (mm)
Coil 1	± 1.4
Coil 2	± 3.5
Coil 3	± 2.1
Coil 4	± 2.7

These figures showed some correlation between the low flatness figures and a low cryogenic load but the actual values, combined with the nominal thickness of 144 mm were well within the maximum permitted size of the vacuum cases (152.4 mm including tolerances). These results were considered to be good, given the amount of machining that was done on the vacuum case forgings: the original thickness and the weight were reduced by 85%.

The in-plane positions of all features were achieved by CNC machining on an 8 m x 4 m double gantry milling machine at a subcontractor (Pro-Mil Engineering Ltd, Birmingham, UK): the project was made possible by such technology. Tolerances achieved in-plane were typically better than 0.025 mm for critical features which is exceptional for components of dimension 5.2 m x 2.7 m.

Load Sensors

One of the essential safety features of the whole system is the monitoring of the out-of-plane loads on all six coils, in service. Excessive out-of-plane (OOP) load would indicate some fault and the power supply will reduce the current to zero until the fault is rectified.

The OOP loads are measured by strain gauged elements which can be replaced whilst the coils are cold and under vacuum. The maximum rating at failure is over 2500 kg each and a sensitivity of ± 20 kg was reached. These sensors performed well and reproducibly with a consistent magnetic load of ≈ 15 kg (total) being indicated at full current. This was due to the magnetic steel used in machinery located about 4 m away from the test area.

Cryogen Supply

The cryogenic supply systems used a static liquid nitrogen tank to provide both liquid and room temperature nitrogen which were mixed to give a controlled flow of nitrogen at a steadily reducing temperature. This was used to cool the coil and radiation screens without exceeding a 30 K differential temperature across each. At 80 K, the coil was cooled to 4 K using transported liquid helium. The overall

cool down process took seven to eight days and was quite efficient cryogenically.

4. CONCLUSIONS

Four coils have now been assembled and successfully works tested. The works tests have confirmed, as far as possible, the soundness and viability of the electromagnetic, cryogenic and mechanical design.

The remaining two coils should be wound, assembled and tested by October 1994. Installation and commissioning of the complete Torus at CEBAF is due to be completed within the first quarter of 1995.

5. REFERENCES

- [1] Ross, J S H, Smith, K D, Street, A J, et al, "Development in the Design of the Superconducting Toroidal Magnet for the Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer", Applied Superconductivity Conference (1992)