Construction and Test Results of an HTS Coil for FRIB Quadrupole

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February 15, 2011

***Abstract*— BNL is developing HTS Quadrupoles in the fragment separator region of the Facility for Rare Isotope Beams (FRIB). Magnets are being made with the second generation (2G) HTS which allows operation at ~50 K. The magnet will be built with a total of eight coils – four with the ~12 mm wide 0.1 mm thick 2G HTS tape obtained from the SuperPower and four with the ~12 mm wide 0.3 mm thick 2G HTS tape obtained from the American Superconductor Corporation (ASC). This note describes the construction and 77 K test results (in liquid nitrogen) of one of the five coils made so far. This particular coil was made with the tape from the American Superconductor Corporation.**

I. MAGNETIC DESIGN

The overall design parameters are given in Table I. The overall design space can accommodate conductors from two vendors (SuperPower, SP and American Superconductor Corporation, ASC) despite a significant difference in the conductor thickness between the two. The magnetic model of one quadrant of the cross section is shown in Fig. 1. The complete 3-d model is shown in Fig. 2. The yoke is warm since it is isolated from the cooler coils to minimize the heat load to be removed at lower temperatures.

TABLE I: DESIGN PARAMETERS OF THE R&D MAGNET

Parameter	Value
Pole Radius	110 mm
Design Gradient	15 T/m
Magnetic Length	600 mm
Coil Overall Length	680 mm
Yoke Length	~550 mm
Yoke Outer Diameter	720 mm
Overall Magnet Length(including cryostat)	~880 mm
Number of Layers	2 per coil
Coil Width (for each layer)	12.5 mm
Coil Height (small, large)	27 mm, 40 mm
Number of Turns (nominal)	125 (ASC for 40 mm), 220 (SP for 27 mm)
Conductor (2G) width, SuperPower	12.1 mm ± 0.1 mm
Conductor thickness, SuperPower	0.1 mm ± 0.015 mm
Cu stabilizer thickness SuperPower	~0.04 mm
Conductor (2G) width, ASC	12.1 mm ± 0.2 mm
Conductor (2G) thickness, ASC	0.28 mm ± 0.02 mm
Cu stabilizer thickness ASC	~0.1 mm
Stainless Steel Insulation Size	12.4 mm X 0.025 mm
Field parallel @design (maximum)	~1.9 T
Field perpendicular @design (max)	~1.6 T
Minimum I_c @2T, 40 K (spec)	400 A (in any direction)
Minimum I_c @2T, 50 K (expected)	280 A (in any direction)
Nominal Operating Current	~140 A (SuperPower), ~370 A (ASC)
Stored Energy	37 kJ
Inductance	~1 H
Operating Temperature	50 K (nominal)
Design Heat Load on HTS coils	5 kW/m^3

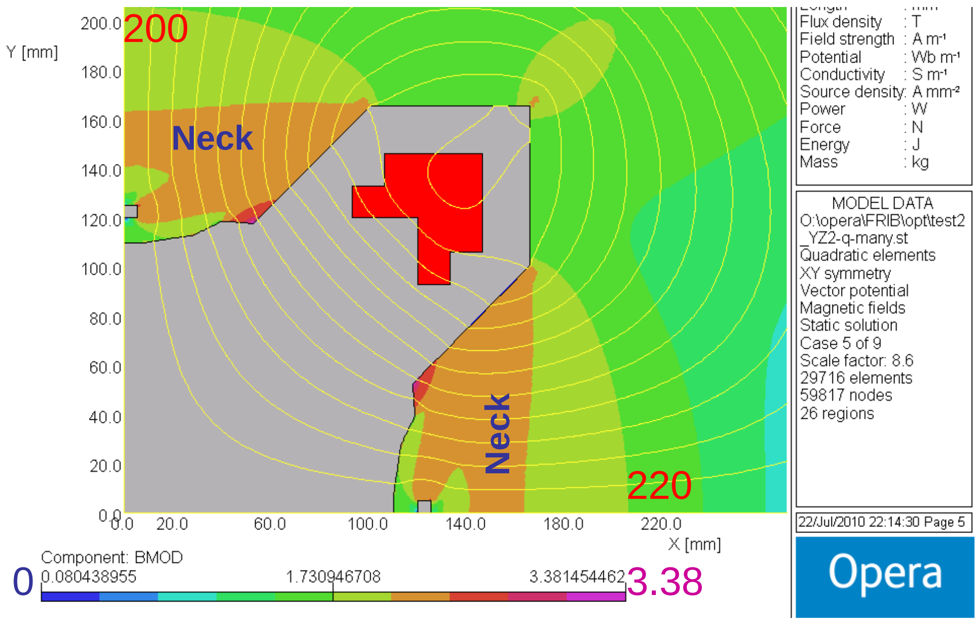


Fig. 1. Magnetic model of one quadrant of the cross-section. Significant effort is made in the design to maximize the iron width in “neck” region of the pole. Field lines and magnitude of the field contour (T) in the yoke are also displayed.

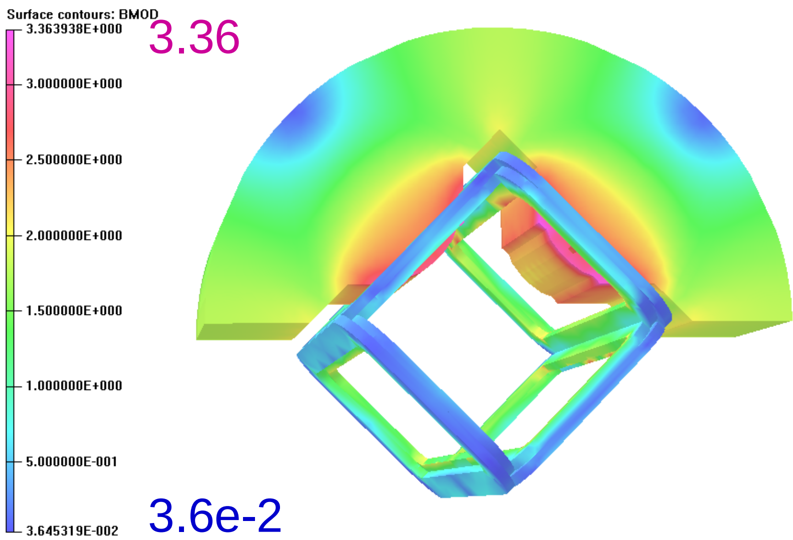
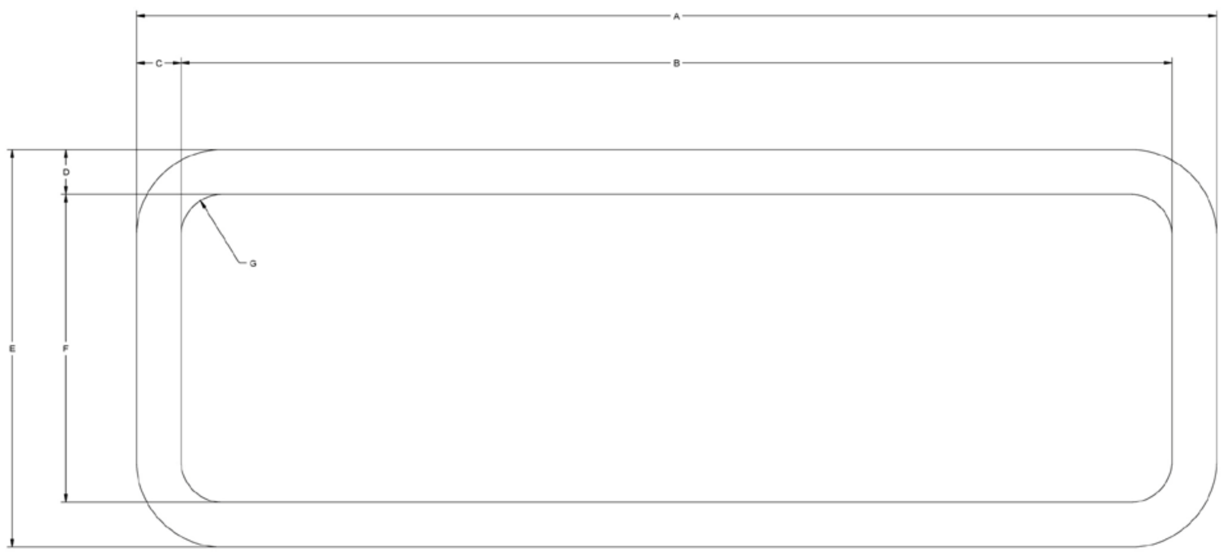


Fig. 2. OPERA 3-d magnetic model with all coils and the upper half of the yoke. The magnitude of the field (T) is superimposed on the surface of yoke and coil. Coils of two heights (26 mm and 39 mm) are nested to maintain the quadrupole symmetry in the cross-section (Fig. 1).

II. CONSTRUCTION OF THE COIL

The coil described here is made with ASC tape which is consisted of two 2G tape and two copper tapes and is sometime referred to as 4-ply tape. The coil parameters of all four types of coils (required two each, total eight for the magnet). All coils having a 40 mm height and a nominal 125 turns are to be made with ~0.3 mm thick ASC tape and 25 micron stainless steel insulation and all coils having a 27 mm height and a nominal 220 turns are to be made with ~0.1 mm thick SuperPower tape and 25 micron stainless steel insulation. The coil tested here is of type "LARGE OUTER COIL". It has a width of ~40 mm. In general, the coils are wound slightly oversized and the correct design width will be obtained after peeling of one or more turn and using appropriate shim. The coil has 126 turns and uses ~210 meter of conductor. Since in the magnet, the magnetic field on this coil will be lower than that in the inner coil, relatively lower performance conductors were chosen for this winding.



ITEM N0.#	A	B	C	D	E	F	G
SMALL INNER COIL	654	600	27	27	240	186	25
LARGE INNER COIL	680	600	40	40	266	186	25
SMALL OUTER COIL	654	600	27	27	266	212	25
LARGE OUTER COIL	680	600	40	40	292	212	25

Fig. 3. FRIB quadrupole is consisted of eight coils, two each of the type listed above in the table (all dimensions are in mm). The coil tested here is of the type "LARGE OUTER COIL" and made with tape from ASC.

Fig. 4 shows the coil being wound and Fig. 5 shows a number of voltage taps to study detailed performance of the coil.

The magnitude of the field on the surface of the coil at 200 Amp is shown in Fig. 6. Field components parallel and perpendicular to the wide face of the tape are shown respectively in Fig. 7 and Fig. 8.

Fig. 9 shows an FRIB coil getting prepared for test in liquid nitrogen at 77 K. Fig. 10 shows the total voltage across the coil as a function of current. Since the coil is made with about 210 meters of conductor, the standard 1 microVolt/cm definition for critical current would mean the total voltage (resistive voltage) across the coil should reach ~21 mV. We stopped measurements at 200 Amp where the voltage across the coil was ~7.3 mV. We believe a more stringent definition (for example, 0.1 μV/cm instead of 1 μV/cm) should be used for HTS magnets. Thus the measured critical current for this coil at 77 K for 0.1 μV/cm definition is 193.4 A in self field. The critical current of the will be different (higher) in the magnet as it will operate at lower temperature (40 K to 50 K) despite a higher field on the conductor.

Fig. 4. An FRIB coil during winding.

Fig. 5. An FRIB coil with a number of voltage taps.

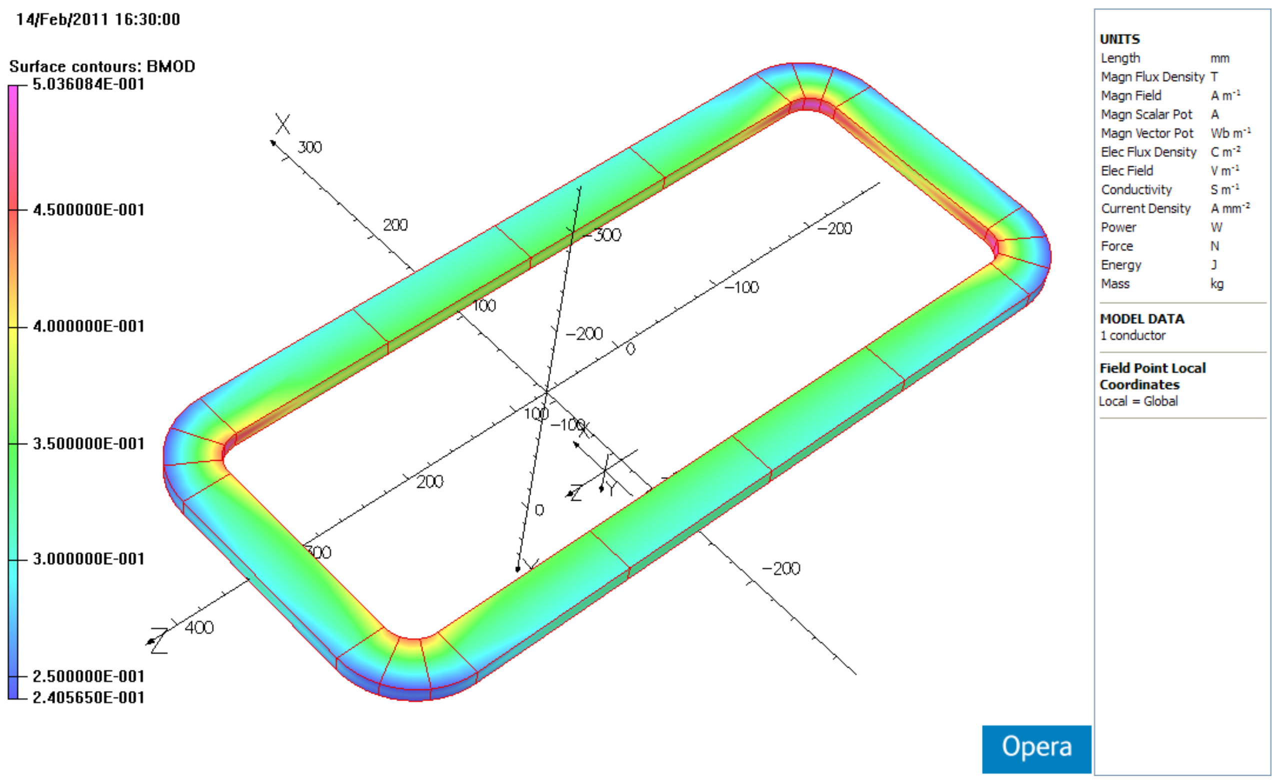


Fig. 6. Magnitude of the field on the surface of FRIB coil (large, outer, 126 turns made with ASC tape) at 200 A.

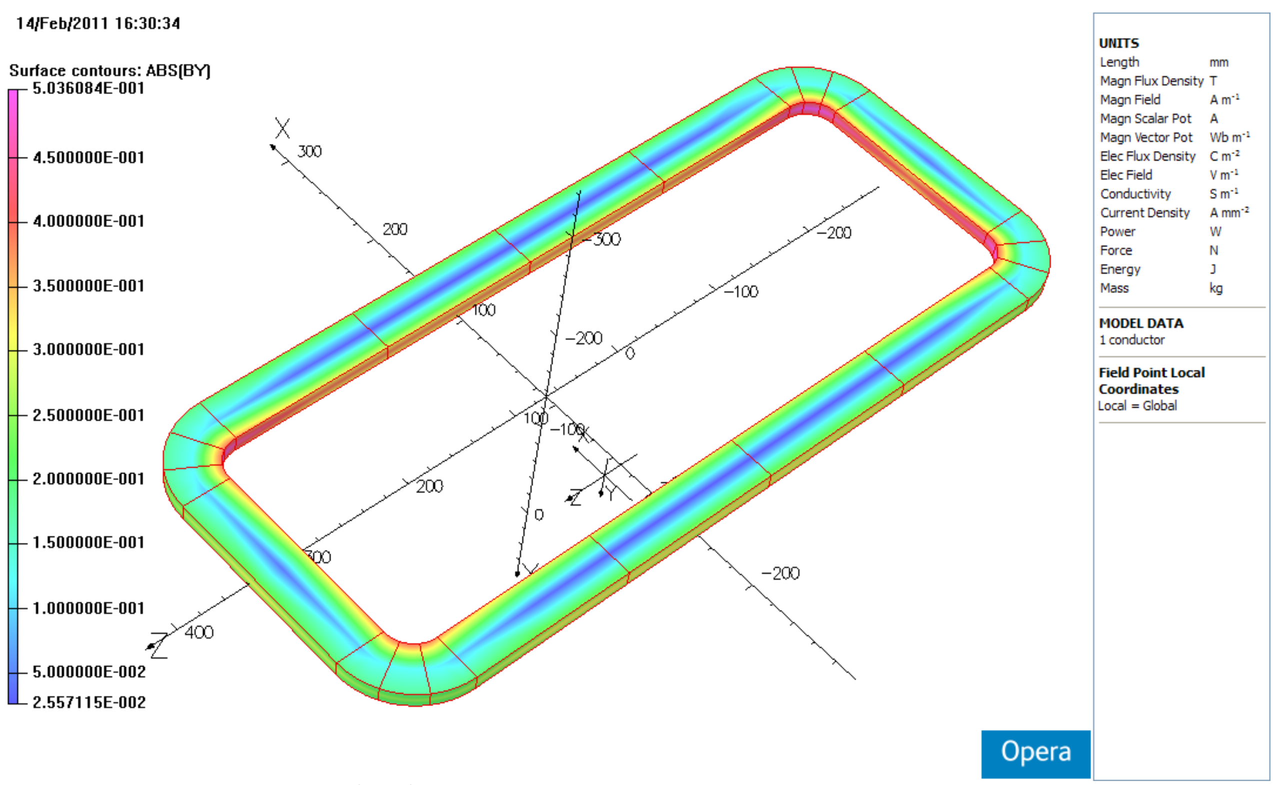


Fig. 7. Field component parallel to wide face of the tape in the FRIB coil (large, outer, 126 turns made with ASC tape) at 200 A.

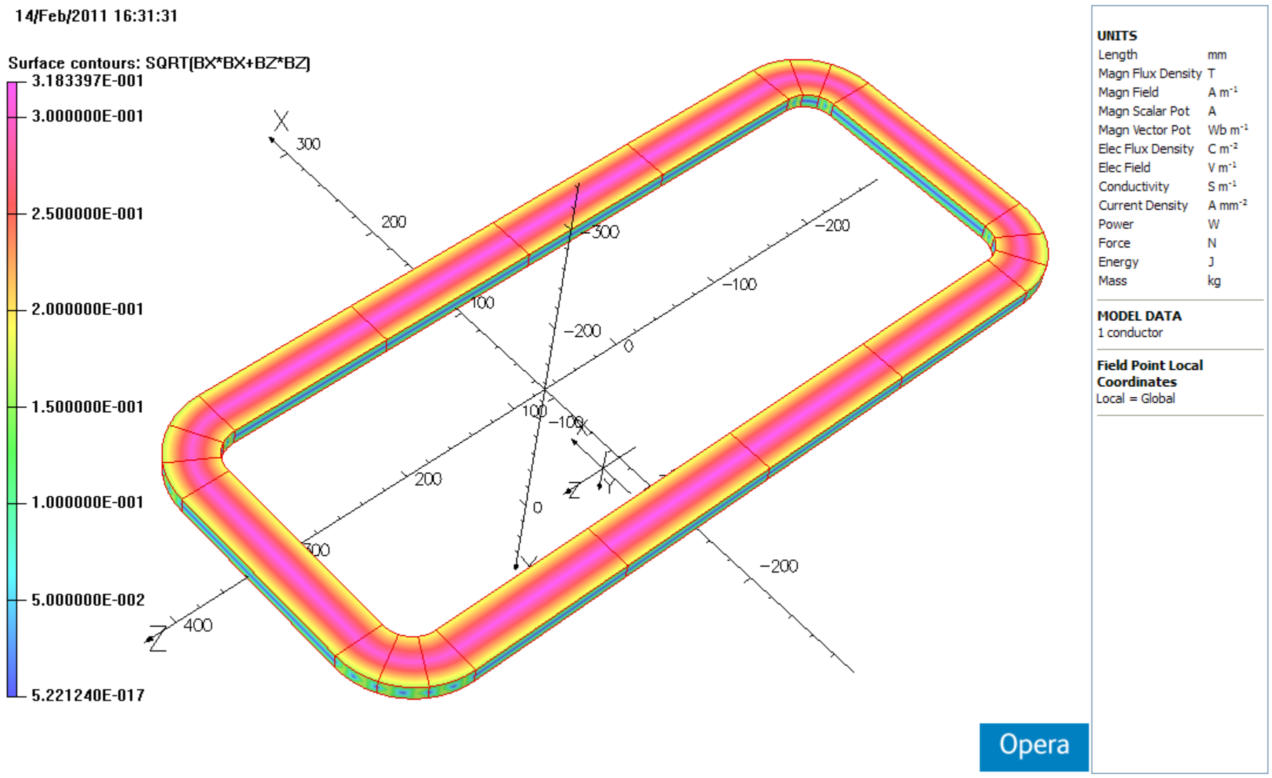


Fig. 8. Field component perpendicular to wide face of the tape in the FRIB coil (large, outer, 126 turns made with ASC tape) at 200 A.

Fig. 9. An FRIB coil being prepared for test in liquid nitrogen at ~77 K.

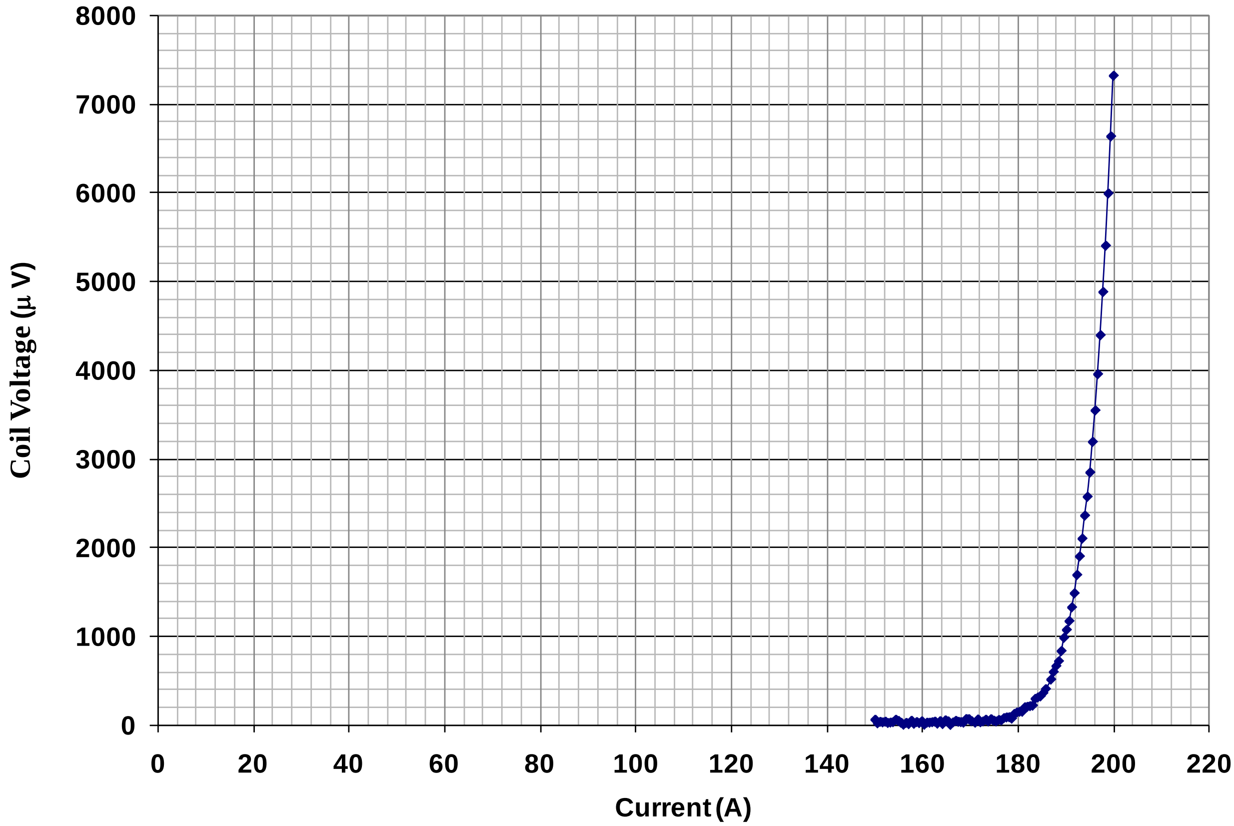


Fig. 9. Measurement in liquid nitrogen (~77 K) of critical current in FRIB coil (large, outer, 126 turns made with ~210 meter tape from American Superconductor Corporation). The critical current in coil with 0.1 μV/cm definition (total coil voltage 2100 μV) is 193.4 A.

III. SUMMARY

Successful construction and test of an FRIB coil at 77 K has been presented. 77 K test is the last and important quality assurance test of the coil. This completes a major milestone of the program. The coil reached 193.4 Amp in self field test in liquid nitrogen and has been found suitable for use in the complete magnet now under construction.