Why a Hybrid Magnet System?

High magnetic field is an extremely valuable tool for benignly investigating the physical, chemical, and biological processes of matter – often, the higher the field the better. In the production of high magnetic fields, cost is perhaps the most fundamental parameter. Cost is itself never a simple issue, but whether one chooses resistive or superconducting technology, the cost to build a large high-field magnet system (the capital outlay) is roughly proportional to the square of the maximum design field. Of course, even the possibility of producing the desired field with a superconducting magnet is limited to something below the critical field of the superconductor at the temperature of operation. For a resistive high-field magnet system, the bulk of the capital expense goes for the power supply that drives it, whereas for a superconducting system, the big-ticket item is the magnet itself.

Operating costs for these two types of systems have quite different character. For a resistive magnet system, the direct operating cost is proportional to the square of the operating field integrated over time. Maintenance adds significantly to operating cost of a resistive system and is also a strong function of time at field. However, when a resistive system is not in use, these costs are practically nil. On the other hand, the operating costs for a superconducting system are dominated by the requirement for cryogenic cooling. These costs accumulate at a comparatively low and steady rate whether the system is at full field or in a standby mode at full readiness, but accumulate they do, and because of the time and effort to cool down or warm up a large superconducting system, there is a strong incentive to hold them either at full standby or fully charged.

In summary, the choice between a purely resistive or purely superconducting system starts with the desired maximum field and how much one is willing to pay to get it. If use is expected to be steady with the field requirement never exceeding the limit of superconducting technology, a purely superconducting system is usually the more economic choice (unless credits can be taken for the flexibility of a resistive system or the cost of the power and cooling systems shared among a number of intermittently used magnets – as is done quite effectively at the NHMFL). If the requirement does exceed this limit, the magnet must be resistive – at least partially.

In a hybrid magnet system, resistive and superconducting magnet technologies are combined – taking advantage of the strengths of each. The superconducting magnet takes the place of the outer portion of the resistive coil, where it is exposed to fields below its limit. The resistive portion operates as an insert to the superconducting magnet and produces that portion of the field beyond the limit of the superconducting magnet (which can be a large fraction of the total field produced). Reducing the requirement for field from the resistive magnet reduces the requirement for power and cooling. A hybrid magnet system is generally the most economical way to achieve the highest steady magnetic fields.

The 45-T Hybrid System, in operation at the NHMFL, produces the highest steady magnetic fields available anywhere in the world – significantly surpassing the 40-T Hybrid at NRIM in Japan, the 35-T Hybrid formerly available at the Francis Bitter Magnet Laboratory in Cambridge, MA and the 30-T hybrids at Grenoble and Nijmegen. In addition, the basis of its superconducting-outsert design on cable-in-conduit conductor technology makes the NHMFL Hybrid significantly more reliable, rugged, and extrapolable than any previous hybrid, thus allowing realistic plans for its upgrade to 50 T with future, higher-power resistive inserts.

The resistive insert of the 45-T Hybrid uses 30 MW of electrical power to produce 31 T on axis, the remaining 14 T being produced by the superconducting outsert. Cooling of the resistive magnet will be accomplished by forced flow of chilled, demineralized water at up to 400 liters per second from the NHMFL plant, which is almost a quarter of the average water flow (averaged over a day) to all the residences of Tallahassee.

The superconducting outsert of the 45-T Hybrid combines Nb_3Sn and NbTi superconductor technology and is one of the largest superconducting magnets ever built – by far the largest superconducting magnet capable of producing a working field greater than 15 T (the outsert is designed to produce over 15 T on axis when operated alone but is required to produce only 14 T when operated in concert with the insert). In addition to the superconductor, the windings of the outsert magnet contain enough steel reinforcement to make 3 automobiles (about 4.7 metric tons) and enough copper for the electrical wiring of 80 average homes (about 3.5 metric tons). A critical requirement of the cryostat design for the supeconducting outsert is that it safely transmit a fault load between insert and outsert of 6 MN, which is approximately 27 times the thrust of a Boeing 747.

General Requirements for the 45-T Hybrid Magnet System

- Versatile – Produce 45 T in a 32-mm bore in the near term using a 24-MW insert, upgradable to 50 T and higher with future, higher-power inserts

- Reliable – Stable under all normal operating conditions, with a 10-year lifetime for the outsert and 600 hours or 2000 charge/discharge cycles for the insert (Normal conditions indude the possibility of a sudden trip of the insert power supply or a failure of the insert magnet)

- User Friendly – Maximize access and use by minimizing obstructions at top of the magnet and by providing for rapid charging

General characteristics of the 45-T Hybrid magnets:

Maximum on-axis field – Combined System, normal operation	45 T
On-axis field contribution by the Resistive Insert	31 T
On-axis field contribution by the Superconducting Outsert	14 T
Maximum field on axis – Outsert only, normal operation	15.4 T
Maximum stored energy	115 MJ
Clear bore – Combined System	32 mm
Clear bore – Outsert only	616 mm
Distance to field center from top of the Magnet Cryostat (Cryostat top is flush with floor in the User Area)	1.2 m
Height of the Magnet Cryostat	2.8 m
Outer diameter of the Magnet Cryostat	2.5 m
Total height of the Resistive-Insert Housing	3.6 m
Mass of the Resistive Insert and Housing	8 t
Total cold mass of the Superconducting-Outsert Subsystem (outsert windings, magnet vessel, in-vessel supports, buses, and cryogenic current leads)	14 t
Combined mass of the Magnet and Supply Cryostats	13 t
Total mass of the combined Resistive and Superconducting Magnet Systems	35 t
Minimum charging time to full field	1 hour
Typical cooldown time	7 days

45-T Hybrid Magnet

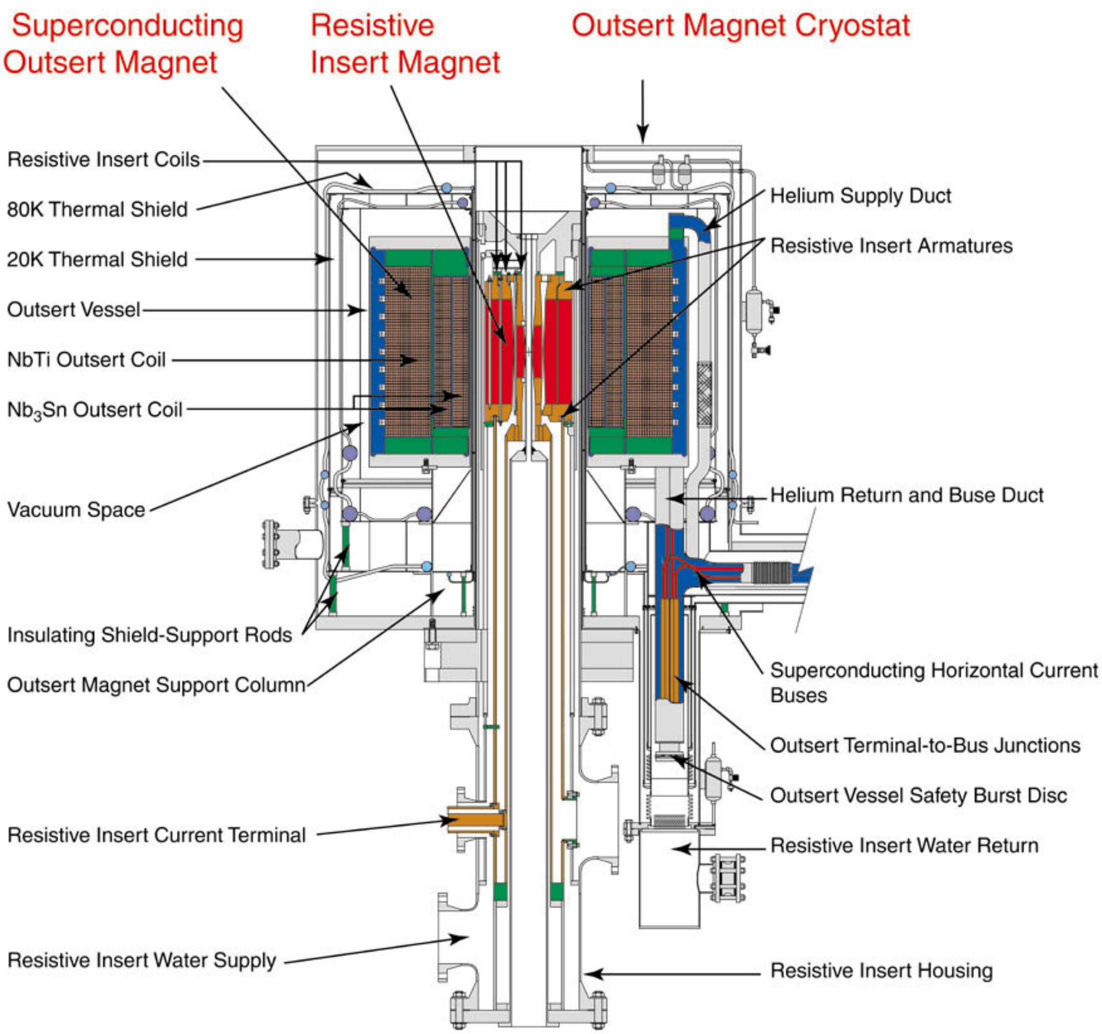

Figure 1 – Cross section of the 45-T Hybrid Magnet. The magnet cryostat is about 8 feet in diameter and the large-diameter part is about 9 feet tall.

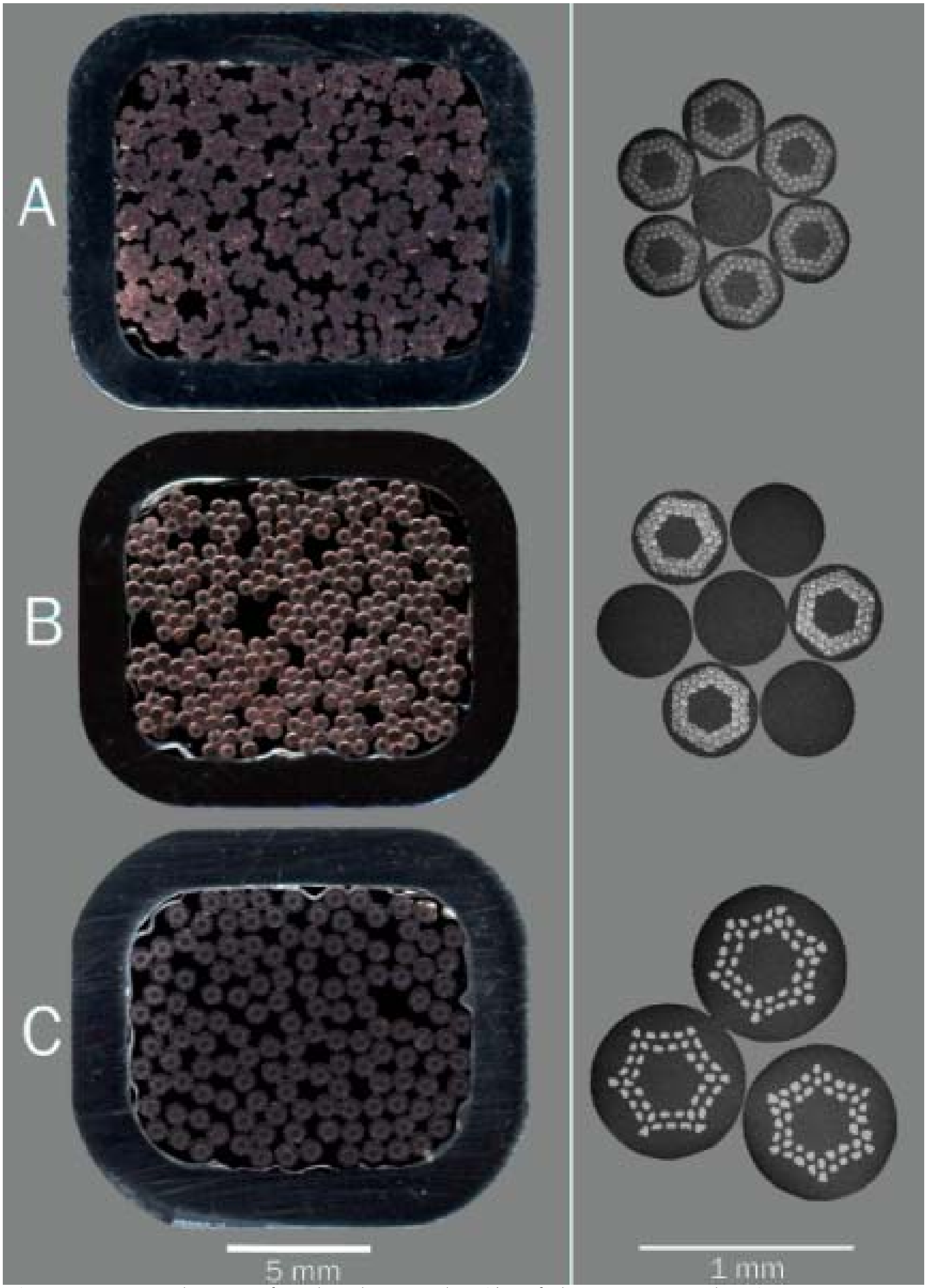

Figure 2 – Conductors for the three subcoils of the Superconducting Outsert Magnet (A, B, and C) were jacketed in special stainless-steel alloys at Gibson Tube. More than 6 km of conductor were used in these coils.