That's a WRAP

A creative wrapping technique builds structurally stable and well-insulated coils for a new fusion reactor.

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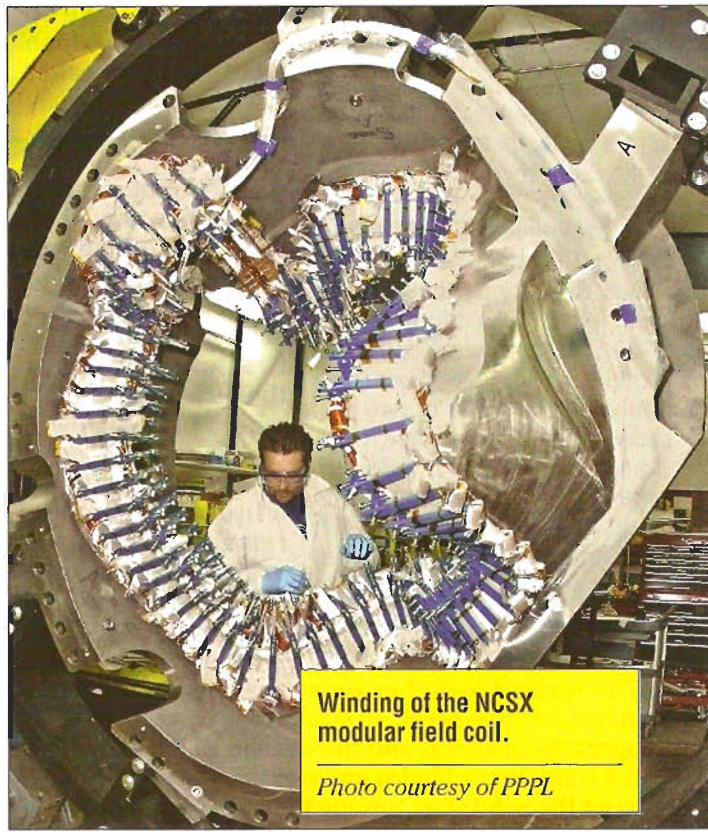
A challenge faced by Princeton Plasma Physics Laboratory (PPPL) researchers was to devise both electrical isolation and structural support for conductive coils that will see 2 kV when the National Compact Stellarator Experiment (NCSX) goes live in 2009. The NCSX produces hot-ionized gases or plasmas confined by a magnetic field. The field is generated by 18 coils made by winding copper cables onto a stainless-steel form.

When the gases reach the right temperature and density, two nuclei fuse together forming a heavier nucleus. The process releases vast amounts of energy. Harnessing this energy provides an inexhaustible electric power source that is safe and environmentally friendly.



Winding of the NCSX modular field coil.

Photo courtesy of PPPL

COILING UP

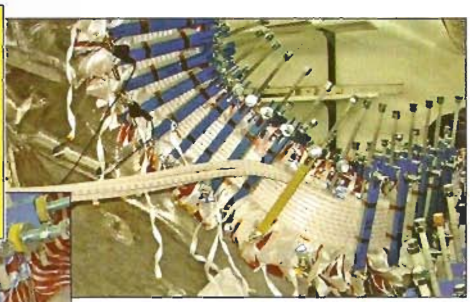
The flexible copper cables are made from over 3,000 strands of 0.0063-in.-diameter wire compacted into a rectangular shape with a cross section of less than 0.15 in.^{2} The cables wind onto the forms in rectangular packs four layers wide and 10 or 11 layers high. The coils must be electrically isolated from the stainless-steel winding form to prevent shorting.

The coils also need a stable support. Unrestrained coiled copper cables would "come alive" when energized and move relative to each other. Even the smallest movement is bad because the magnetic field in the Stellarator device depends, in part, on the shape and position of the coils. Movement could also damage the coils and shorten their life.

Two critical elements provide the required electrical isolation and stability. One is an electrical-insulation material (ground wrap) wrapped around the copper cables. The other is a hard epoxy that encases the flexible cable-and-insulation assembly in a solid structure and gives some additional electrical insulation.

For the insulation material, designers had a choice between Mylar and Kapton tape. Both provide needed electrical isolation. But Kapton, a polyimide film, better withstands cryogenic temperatures during NCSX operation without turning brittle or losing critical properties. Temperature was also a factor in selecting epoxy. It must hold up under liquid-nitrogen operating temperatures without cracking.

Although Kapton has enough insulation for the copper cables, it posed a design challenge. The polyimide film won't absorb epoxy and would remain flexible. It was also not thick enough (0.005 in.) to insulate adequately. **Fabrico Inc.,** helped solve these issues. Fabrico is a contract design and manufacturing firm specializing in the conversion of flexible materials. Its engineers helped develop a conservative ground wrap



Ground wrap went on the coil winding form in multiple half-lapped layers. Insulated copper rope then wound onto the winding form on the top half of the insulation material.

Photos courtesy of PPPL

that not only meets insulation requirements for normal operation at 2 kV but also withstands errant voltage spikes as might come from a fault in the electrical system.

The ground wrap consists of a fiberglass layer attached to the Kapton tape. Fiberglass easily absorbs epoxy and helps it flow into the innermost parts of the coil. Once hardened, the epoxy-reinforced fiberglass on the Kapton tape provides the required structural support for the coils. Fabrico is one of the few fabricators able to join Kapton tape and fiberglass. S-glass was chosen for the NCSX coils. It is stronger and less expensive than E-glass, and is treated in a way that improves its ability to absorb epoxy. S-glass also has a slight edge over E-glass in withstanding exposure to radiation. This is important because fusion devices such as NCSX are radioactive during operation.

Conservative insulation design called for extra-thick 5-mil (0.005-in.) Kapton tape. But 5-mil Kapton tape is exotic and particularly difficult to obtain. As an alternative, Fabrico suggested laminating together two layers of more readily available 2-mil (0.002-in.) Kapton tape. Any current spikes would generate magnetic forces on the coils. Wraps had to allow for such effects by adding structural reinforcement.

The insulation design required ground wrap to go on the coil winding form in multiple half-lapped layers — each strip covering roughly half of the strip laid down before it. With the ground wrap so positioned, the fiberglass layer had to be wider than the Kapton tape to expose the glass. If fiberglass didn't extend past the ends of the tape, the overlapping of the insulation layers might have made it difficult for epoxy to reach the glass. This would have reduced structural stability.

The ground wrap went on the coil winding forms with the Kapton side facing the copper cables. One end of each insulation strip attached to the winding form, while the other end was temporarily free. The copper cables were wound onto the steel forms over the top half of the insulation strips. With the cables in place, the free ends of the insulation strips were folded up and brought together with the attached ends so the ground wrap completely covered the cables.

In the final step, a tight-fitting rubber mold enclosed the copper cable and ground wrap. This assembly then went in an autoclave. Under vacuum, technicians filled the mold with epoxy. Over 8 hr the epoxy worked its way between the strands of the copper cables, completely wetting the insulation materials, and filling the voids around the coiled cable.

The epoxied assembly cured in the autoclave or in a vacuum oven at 110°C for 5 hr followed by 15 hr at 125°C. **MD**

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