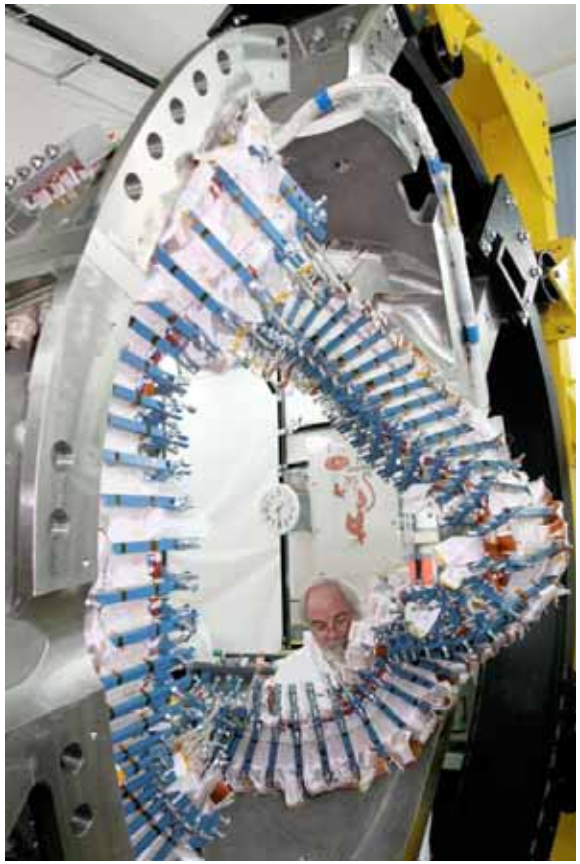
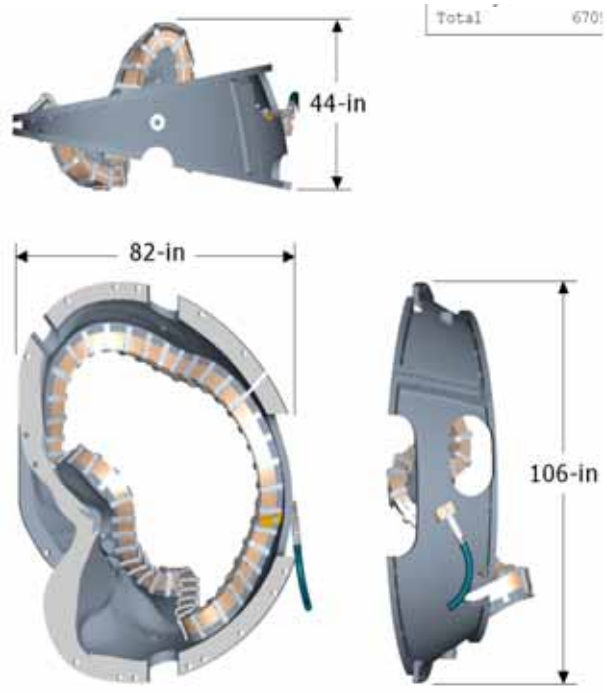
Modular Coil Manufacturing

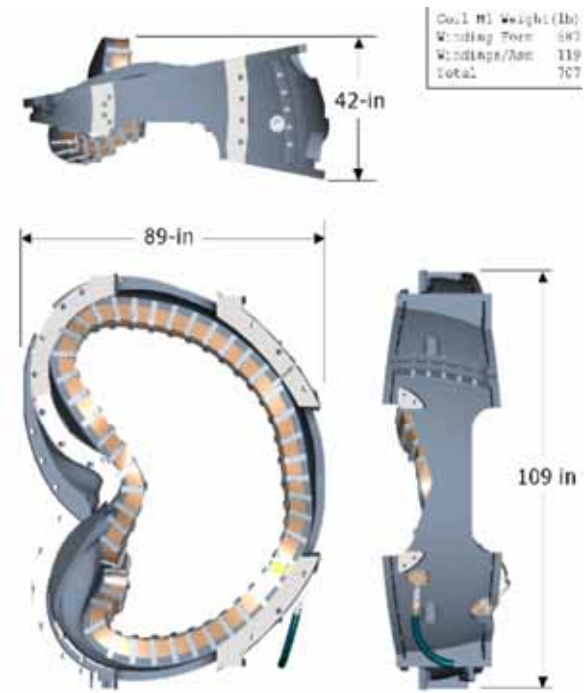


J. H. Chrzanowski for the NCSX Project

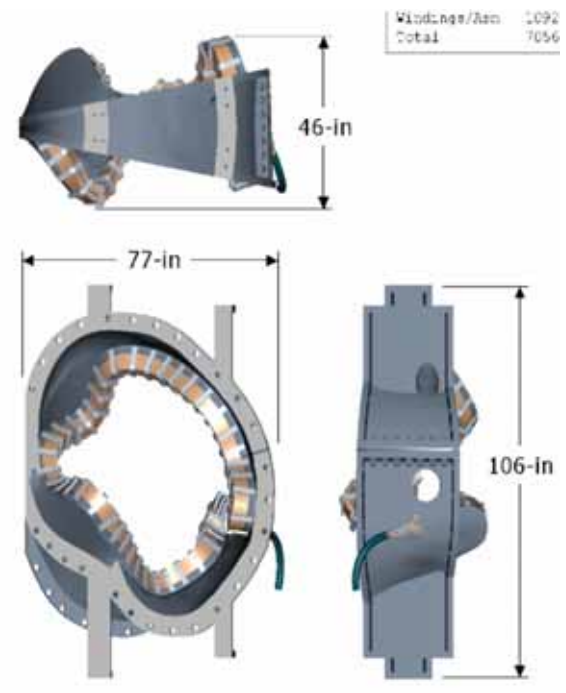
Modular Coil Types



Type A



Type B



Type C

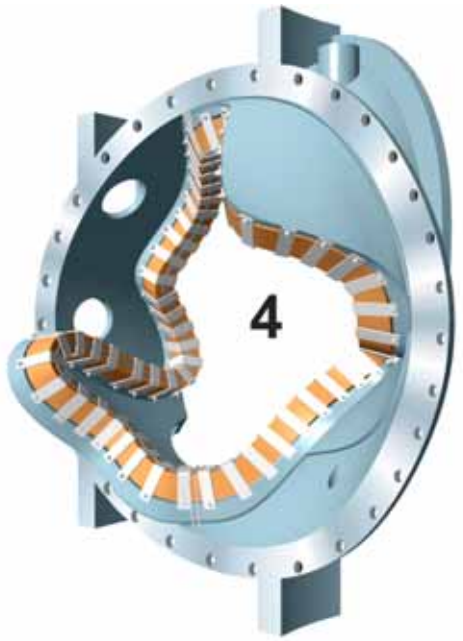
Winding form weight: approx 5400 lbs
Finished weight: approx. 6600 lbs

PHASES of MODULAR COIL FABRICATION

- **Custom alloy similar to CF8M (cast 316LN) Stel-alloy**
  - **Low permeability ($\mu < 1.01\mu_0$) & good structural properties at operating temp.**
- **Provides continuous support for strength and accuracy of winding**
- **Single machined part provides winding form and assembly features**
  - "Tee" machined to follow physics-specified coil trajectory within ±0.25 mm.
- **Winding never removed from coil form**

Castings fabricated & machined by outside vendor

Coils wound and VPI by PPPL



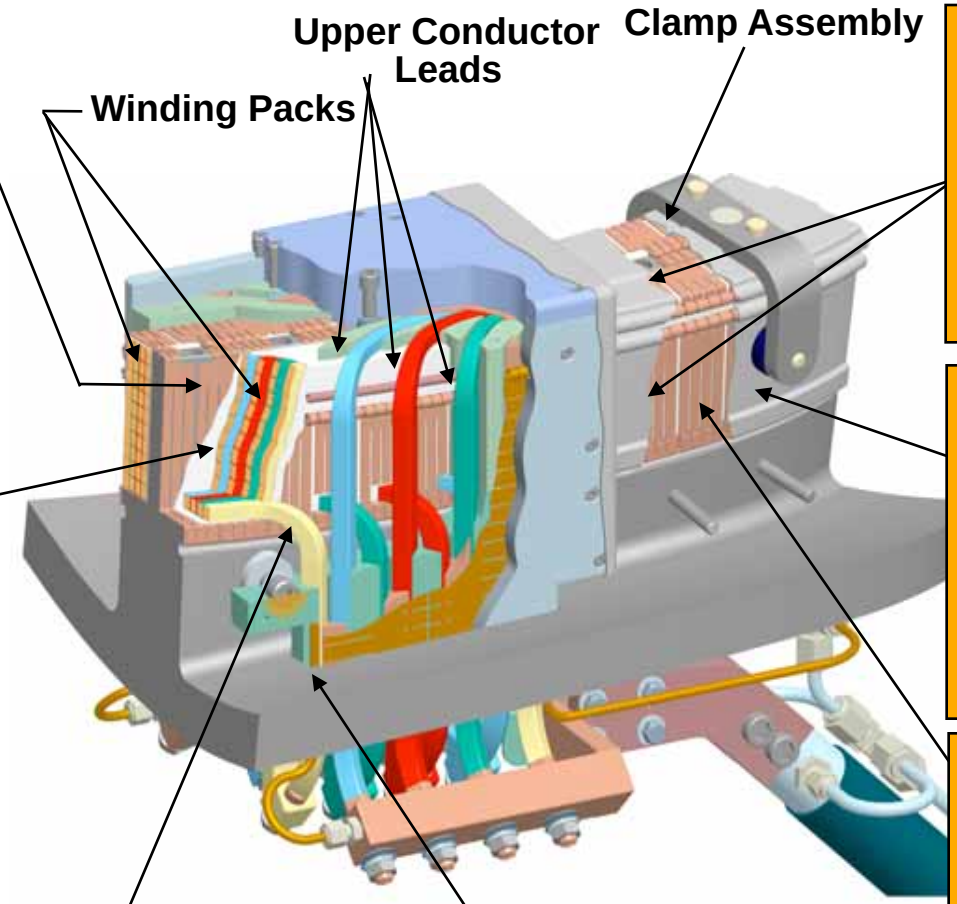
Modular coils tested and ready for installation

Manufacturing Steps for a Modular Coil

Step 1: Installation of the copper chill plates onto the winding form.

Step 2: An outer wrap of fiberglass cloth is installed and the conductor layers are laid in place.

Step 3: Special winding clamps are used to hold the conductors during the winding.



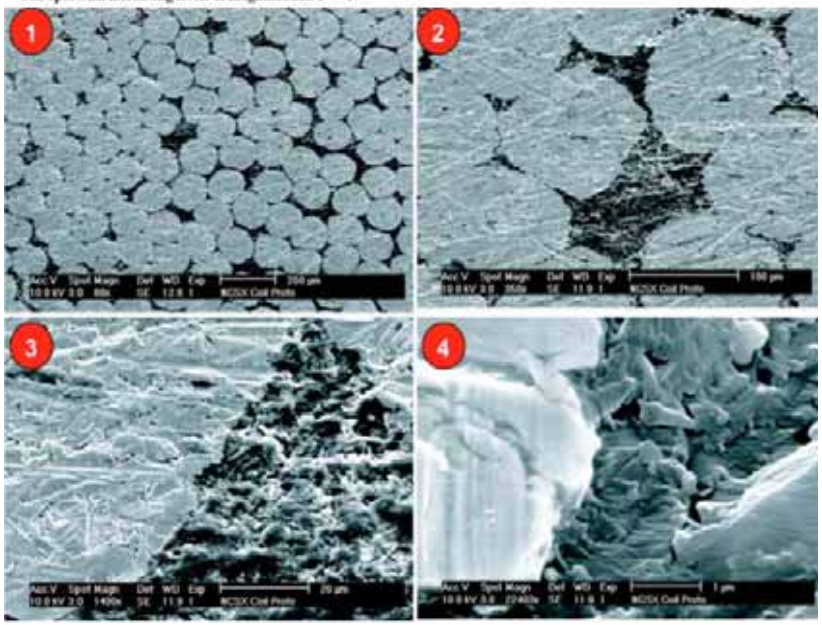
Step 4: Outer copper chill plates are installed. And cooling lines attached.

Step 5: A silicone bag is built around the coil. This is the mold for the VPI process.

Step 6: Epoxy/Glass Shell mold applied over silicone bag

Modular Coil Conductor

- **Flexible copper “rope” conductor wound onto “tee”-shaped guide on the MCWF.**
  - The rectangular compacted copper conductor will be fabricated using 34-gauge oxygen free copper wire. Its rope construction is [12 x 5 x 44 x 34] with an external 0.004-inch thick nylon serve.
  - Once cabled, the copper rope was compacted to dimensions of 0.350 in. x 0.391 in. +/- 0.010 inches. [Note: dimensions include the nylon serve].
  - The vendor then applied (2) half-lapped layers of dry S-2 glass insulation around the completed conductor.
  - Conductor supplied by New England Wire Technologies, Inc.
- **Conductor trials demonstrated good epoxy fill between strands**



R&D Winding/VPI Development

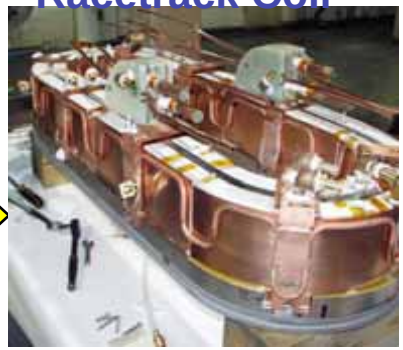
Univ. of Tenn. Coil

First use of selected epoxy system for VPI

Straight Tee Section

First use of "Bag Mold" -VPI

Racetrack Coil



First winding experience & use of copper cladding

Production Coils

First use of final manufacturing processes

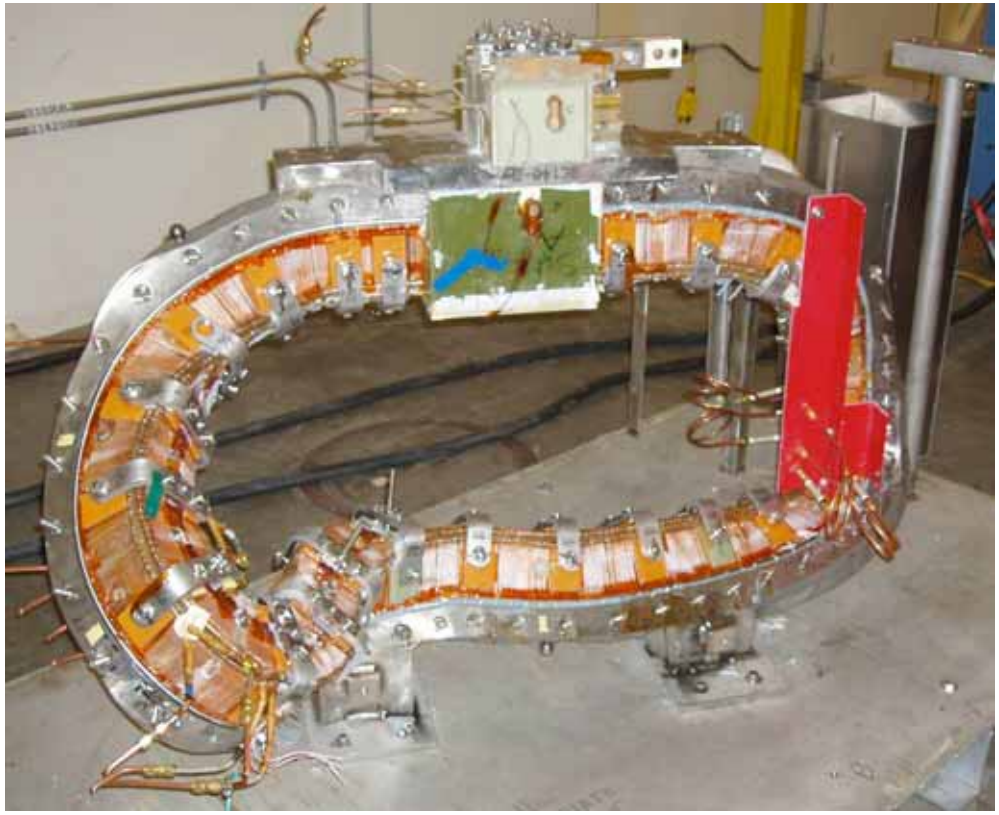
Twisted Racetrack Coil

- Develop winding & metrology techniques & tooling
- First use of autoclave for VPI

Inch-Worm Winding

- Develop conductor handling methods
- Train crews
- Develop procedures

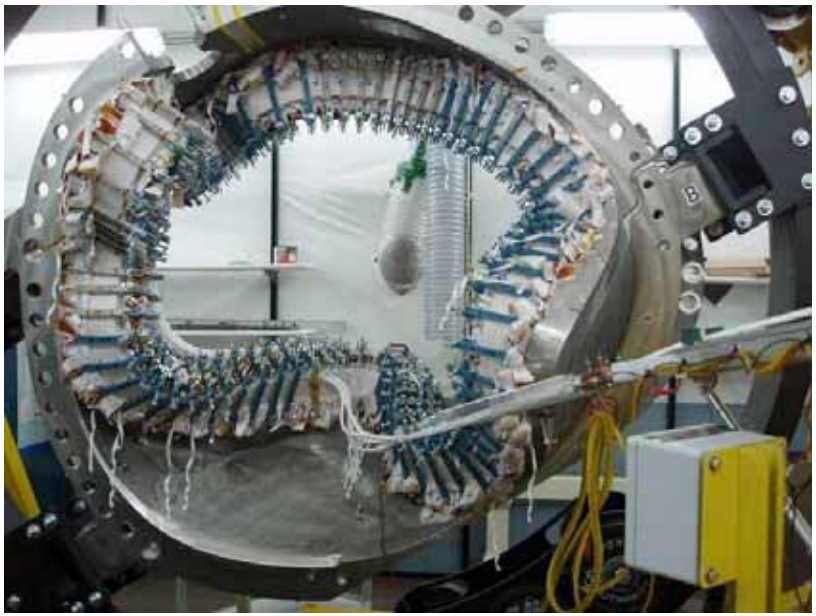
Twisted Racetrack (TRC) Accomplishments



- **Manufacturing lessons learned:**
  - Tolerance control
  - Manufacturing procedures
  - Tool development
  - Verification of the VPI plan
  - Training of key personnel
- **Testing results:** [**Exceeded insulation design requirements**]
  - Verification of thermal performance [single phase liquid nitrogen -81 °K**]**
  - Operating current at 31.5 KA
  - Verified integrity of electrical insulation:
    - >10 KV groundwall
    - >5 kV turn to turn

Modular Coil Winding Fixture

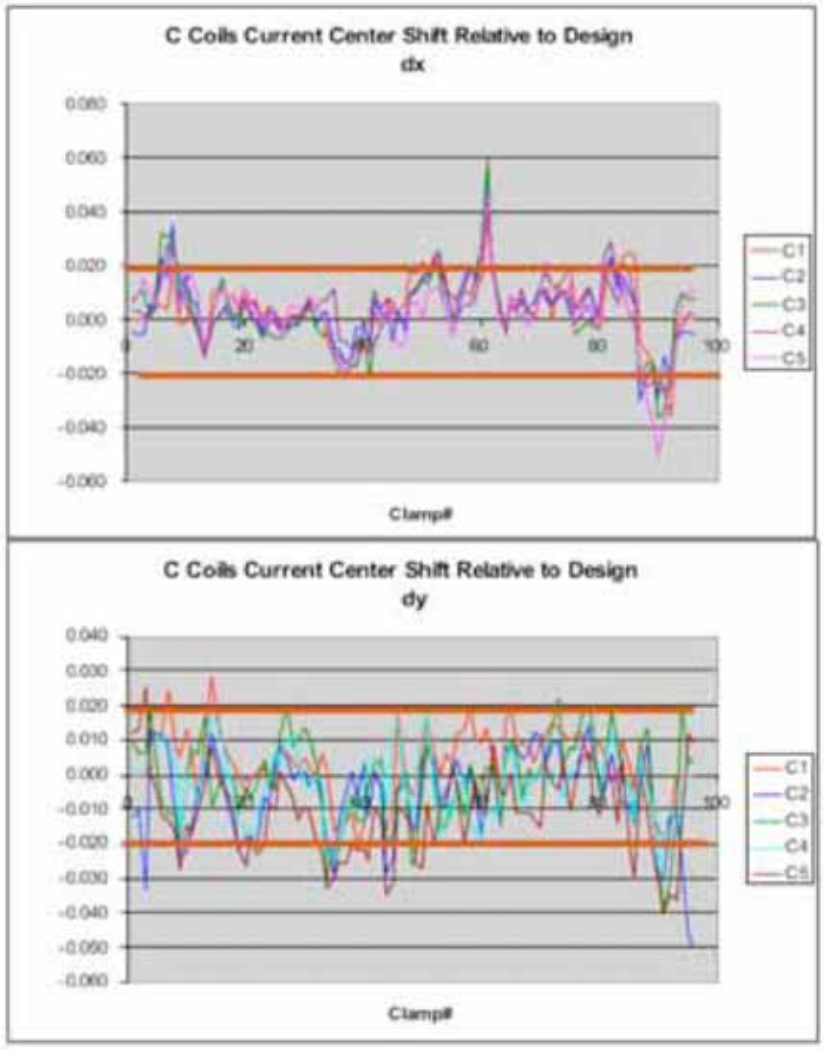
- Coils were wound on vertical turning fixture that allowed for operations to be performed on both sides simultaneously
- Turning fixture also served as modular coil lifting fixture



Modular Coil Winding Activities

Maintaining Required Tolerance

- **Flexible copper "rope" conductor wound onto "tee"-shaped guide on the MCWF.**
  - "Tee" machined to follow physics-specified coil trajectory within ±0.25 mm.
  - Small conductor (9x10 mm), wound 4-in-hand, minimizes keystoning.
  - Winding pack dimensions are measured with portable CMM and adjusted with clamps to position current center within ±0.5 mm.
  - Turns are temporarily held in position using glass tape [Lacing]

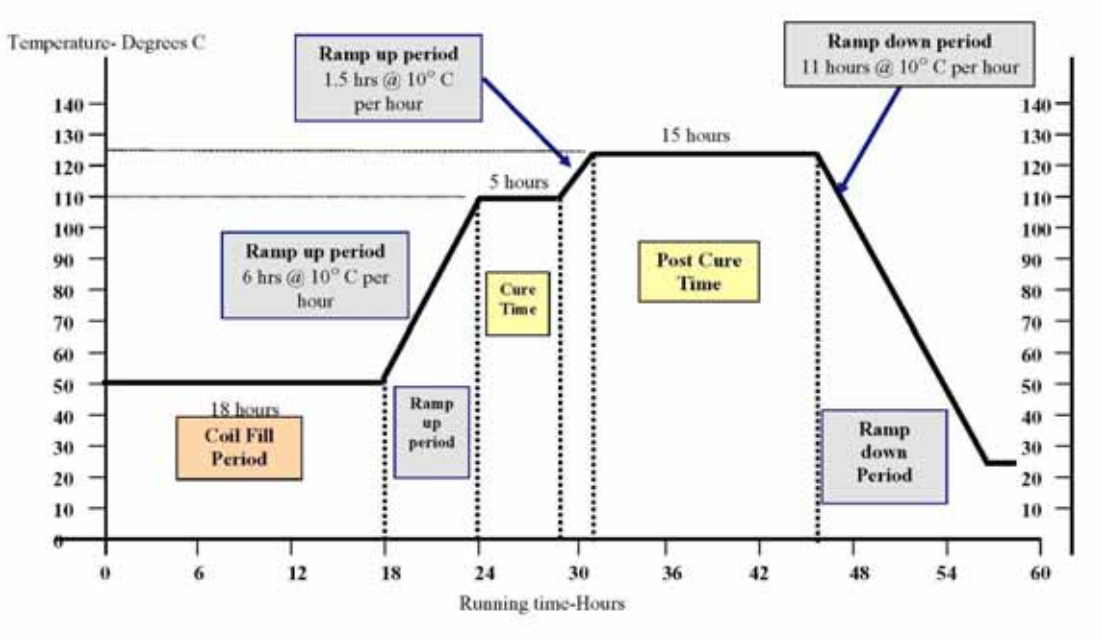


Bag Mold Method

- **"Bag Mold"** : is a mold where high tolerance outside dimensions are not required; it can accommodate more difficult configurations. It is constructed using silicone bag for vacuum boundary and chopped fiberglass and epoxy for the structural shell

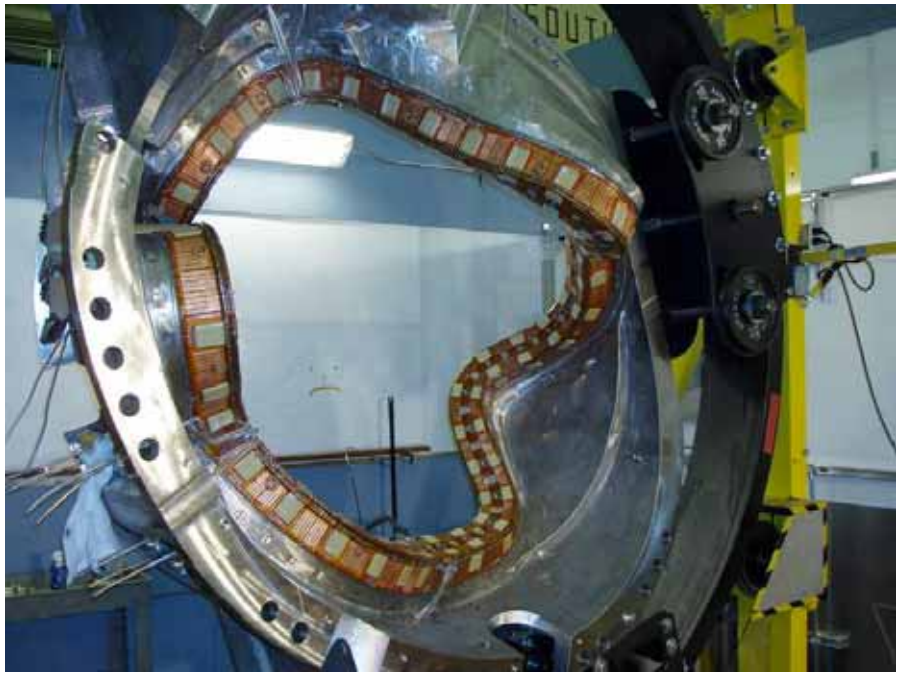
VPI Activities

- VPI was performed in autoclave
- Multiple epoxy feeds were used to ensure total fill
- Approximately 6 hours to fill coil
- Eleven gals of epoxy to fill coil/ 22 gals mixed
- VPI operation takes approx. 60 hours:



Post VPI Activities

- Once coils have been VPI'd the bag mold is removed, final coil clamps, thermocouples are then installed and the coils were electrically tested to 7.5 kV



Removing bag mold & shell

Final Coil Clamps

In Summary....

- ***18 modular coils have been successfully wound, VPI'd and tested***
- ***Close to 3 years to complete the winding and VPI of the modular coils***
- ***Metrology played an enormous part of the operations***
- ***All technological challenges were successfully addressed.***
- ***Safety was in the forefront of all planning and performance of field activities***