PPPL digest
PRINCETON PLASMA PHYSICS LABORATORY
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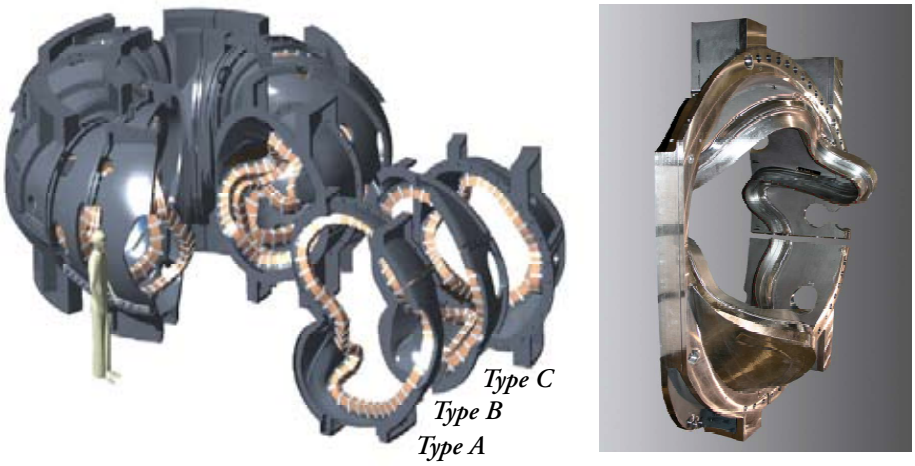
Advanced Technology Essential in NCSX Component Fabrication

An Interview with Phil Heitzenroeder

The National Compact Stellarator Experiment's 18 modular field coils are among the most complex, innovative electromagnets ever designed. Six each of three coil types are being fabricated. The 18 winding forms consist of nonmagnetic stainless steel castings with winding surfaces machined to a tolerance of ± 0.010 inch. The largest winding form is 109 inches tall. Each form weighs approximately 6,000 pounds. The winding forms are the structural backbone of the modular coils system and are strong enough to support electromagnetic loads as high as 7,000 pounds per inch of coil.

The PPPL NCSX Coils Group.

Fabrication of the NCSX modular field coils is underway in the former Tokamak Fusion Test Reactor (TFTR) Test Cell. The conductor is fabricated using a flexible copper cable with approximately 3,420 strands of bare 0.0063-inch diameter wire compacted into a rectangular shape 0.35 x 0.391 inch. The rectangular conductor is insulated with two half-lapped layers of 0.004-inch fiberglass cloth. The conductors are wound onto the forms in rectangular packs, four layers wide and either 10 or 11 layers in height de-



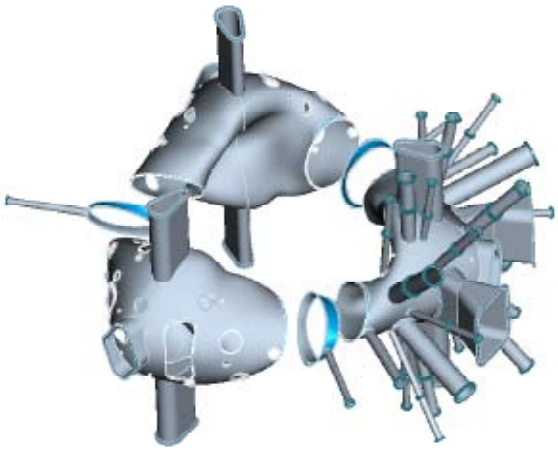
The NCSX Modular Coil System, shown above, uses six each of three coil types. The photo on the right shows the first machined modular coil winding form.
(Photo courtesy Energy Industries of Ohio (EIO) and Major Tools and Machine, Inc.)

pending on the coil type. The winding tolerance for the current center of each coil is ± 0.020 inch. Each coil uses 1,600-1,900 feet of conductor, depending on the coil type.

The 18,000-pound NCSX vacuum vessel, which will be located in the bore of the modular coils, resembles a twisted doughnut. It is made of Inconel 625, an alloy that is hard to form, but chosen because of its high electrical resistivity that will suppress electrical currents that might interfere with plasma confinement. The vessel was press formed with 0.375-inch walls and has a tolerance of ± 0.188 inch. It was fabricated in three identical segments, which will be welded together end-to-end at PPPL during final assembly. The vessel has approximately 100 ports that will provide plasma heating and diagnostic access.

The precision with which these intricate and complex parts are being fabricated is pushing the state of the art. PPPL visitors who have recently toured the former TFTR test cell have expressed their fascination at the marriage of computer and machining technology being employed. Consequently, we invited Phil Heitzenroeder, who is the Technical Representative for the Modular Coil Winding Form procurements and who heads the PPPL Mechanical Engineering Division, to share with us how new technological processes are making possible the unique fabrication and eventual assembly of NCSX.

PPPL Digest: Coil fabrication capabilities have come a long way since the 1970's when you came to PPPL. What are some of the major differences?

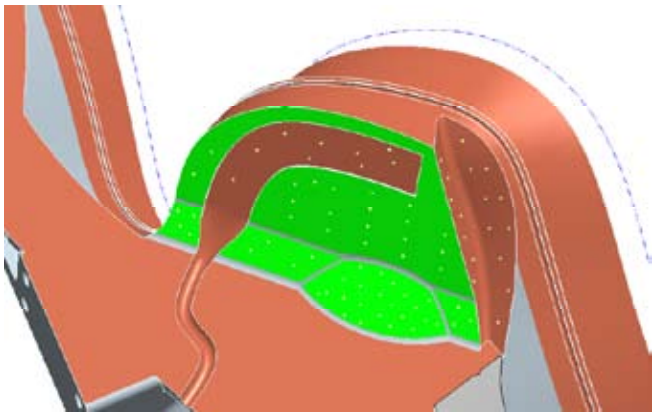


A CAD Model of the vacuum vessel and the vessel segments during fabrication.
(Photo courtesy EIO and Major Tools and Machine, Inc.)

Phil Heitzenroeder: There have been several major areas of advancement in engineering and manufacturing that have greatly benefited coil fabrication. The most important are 3-D Computer Aided Design (CAD) and Computer Aided Machining (CAM) that make it practical to design and manufacture complex, 3-D coils and parts like those needed in a stellarator. Complementing these are advances in measurement technology — metrology—that make verification of the dimensions of large, complex parts and precision assembly possible. There are a variety of types: laser trackers, laser scanners and Coordinate Measuring Machines (CMM). Advanced analytical techniques were custom developed for NCSX by engineers and physicists at PPPL and Oak Ridge with inputs from colleagues at other laboratories. These, along with commercially available electromagnetic analysis programs, were needed to develop the CAD models, which became the starting point for our industrial partners. The analytical work behind the design is quite remarkable. In the case of NCSX these high technology techniques were absolutely essential. We could not have made this machine in the 1970's, because these capabilities — along with the ability to analyze them — did not yet exist.

PPPL Digest: Describe the process for manufacturing the NCSX Modular Coils.

PH: It's almost a paperless process. We load the CAD models onto a computer file server along with a few drawings that contain notes and a few basic dimensions and tolerance information. Our subcontractors then download these files at their location and use this information to develop CAM programs that provide instructions to the milling machines. Contractual information such as the Statement of Work and Specifications are also located here; much of our communication is by e-mail. This computer-based system permits effective communication between PPPL, our project partners at Oak Ridge National Laboratory (ORNL), and our subcontractors. We'd really be at a loss if we did not have the internet.



The Internet and CAD…Perfect together! The CAD image above illustrates one of the typical exchanges between PPPL, ORNL, and EIO. This visual representation of data permits clear and efficient communication among us.

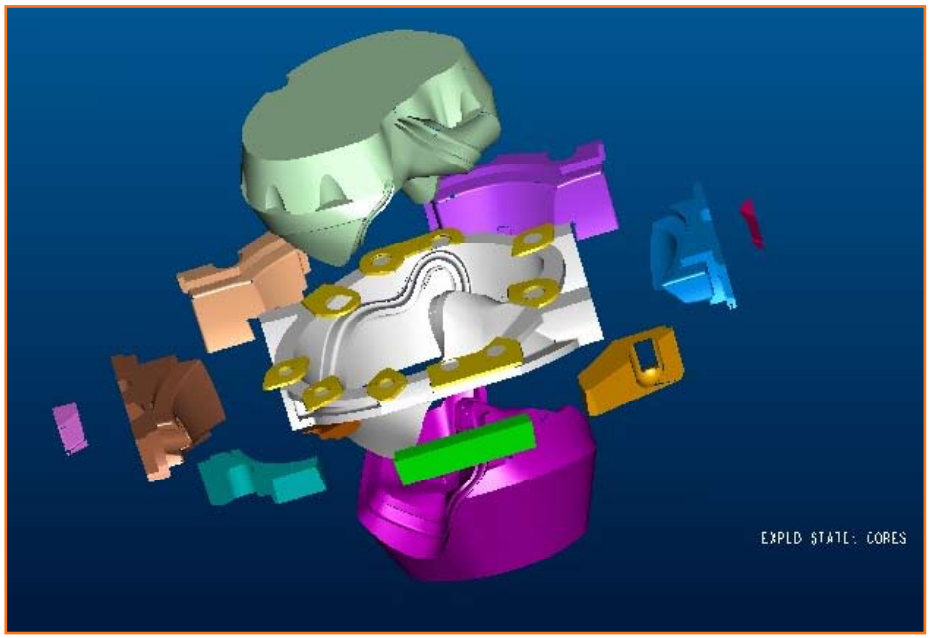
A cast-and-machine process is used to manufacture the modular coil winding forms. Sand casting is a centuries-old process in which molten metal is poured into sand molds, which have hollow cavities that have the shape of the part. It's fundamentally simple, but to produce high quality, geometrically complex, large parts such as the winding forms, high technology techniques are needed. Several high tech processes were used in making the winding form molds: CAD, flow/solidification analyses to guide the mold design, CAM, and laser scanning and CMM to measure this complex geometry. Details of the manufacturing process illustrate how essential these high technology additions were to producing these parts.

The molds are made by packing sand mixed with binder around patterns which, after removal, leave cavities of the shape of the parts and provide passages to pour in the molten metal. A sand mold can only be used once, since it is destroyed during the casting process. The high sustained heat from the molten metal weakens the bonded sand, and cool-down contraction of the steel begins to break up the sand mold. After the part cools, the remainder of the mold is broken up to remove the casting. Consequently, a mold is needed for each casting. Using patterns to form

the molds for each casting type assures that all of the castings produced are near replicas.

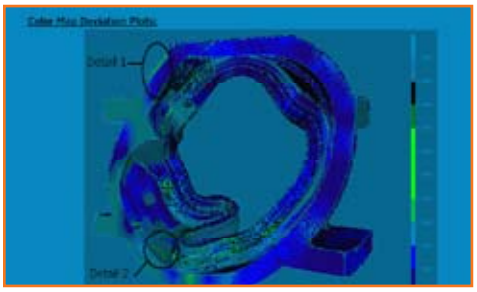
The patterns for the NCSX winding forms are very large and complex, and designing them was an involved process. They were contour milled from large laminated blocks of mahogany using CAD models which were dimensionally adjusted to compensate for thermal contraction of the casting as it cools from its pour temperature in excess of 27,000°F to room temperature and to provide additional metal ("padding") for machining allowance and to assure that the final part can be machined from the casting. The patterns also needed to include molten metal reservoirs ("risers") and plumbing ("gating") to assure an adequate supply of molten metal as it cools and shrinks. The patterns also contain insulation and heat sinks in select areas to control temperature differences in the casting. The dimensions of the patterns were verified by laser scanning, as shown on page 5 (top).

The number and placement of risers, insulation, heat sinks ("chills"), and the piping connecting the risers and mold together ("gating") are determined through iterative flow/solidification analyses. The goals of these analyses are to

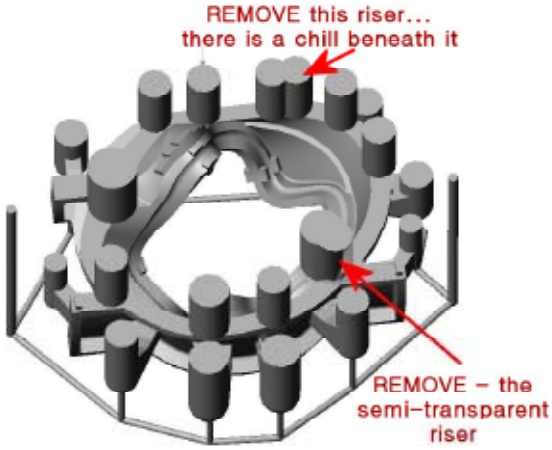


An exploded view of one of the three pattern models and photos of pattern pieces during fabrication.
(Photos courtesy of EIO and C.A. Lawton Co.)

achieve controlled directional solidification of the part and assure adequate make-up molten metal during cool-down to avoid shrinkage voids and defects in the casting. These analyses have proven to be quite effective in the case of NCSX.



Laser scanning verifies the pattern's dimensions and the dimensions of the first part casting.
(Photo courtesy of 3D Scanco)



Flow/Solidification Analyses guide the mold and pattern design (Courtesy EIO/CA Lawton Co./MetalTek, Inc.)

After the casting cools and is removed from the mold, the risers and gating are cut off and the casting is dimensionally inspected using a laser scanning process. A number of operations follow this: clean-up of cast surfaces; magnetic permeability checks of the casting; lab verification of the alloy properties; X-ray inspection to check for internal flaws; heat treatment; die penetration inspections to check for surface flaws; and "upgrading" (weld repairs) as required to repair flaws exceeding specified limits. The casting weight at this point is about 8,000 pounds., leaving about 2,000 pounds. to be removed during machining.

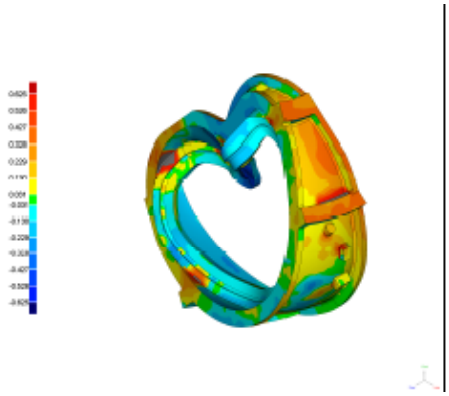
Pouring of a casting. The assembled mold, along with its surrounding steel reinforcement called a cask, is shown; it weighs about 30 tons. During the casting pouring process, about 22,000 pounds. of molten stainless steel was poured. Following days of preparation, the pour was finished in about 1.5 minutes.
(Photo courtesy of EIO and Metal Tek, Inc.)

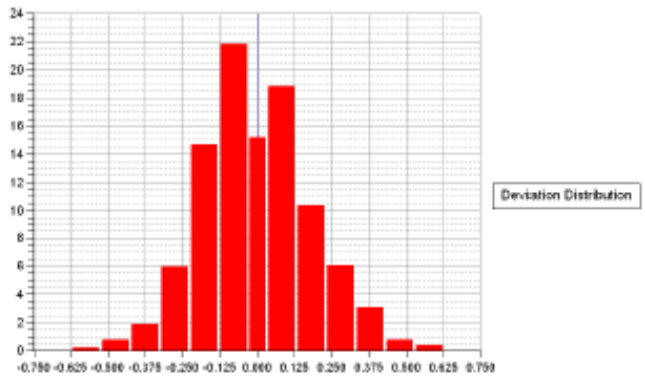
The unveiling of a new casting with some of the risers still in place.
(Photo courtesy of EIO and Metal Tek, Inc.)

A variety of multiple multi-axis milling machines using custom-engineered compact cutting tools with long reach are necessary to machine the complex winding form geometry. *(Photos courtesy EIO and Major Tools and Machine, Inc.)*

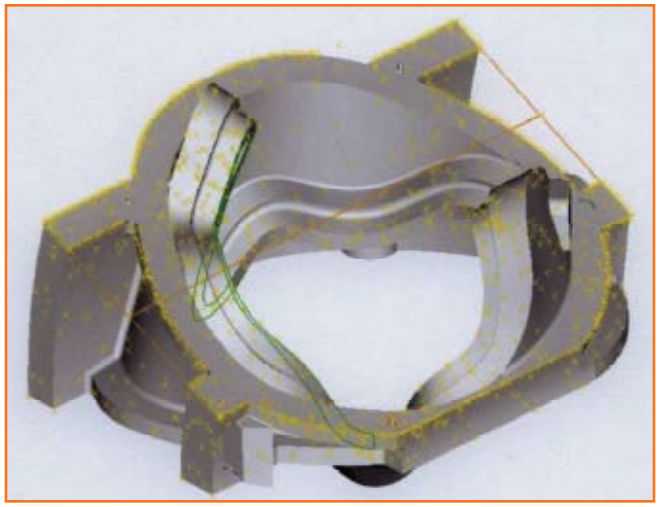
One of the most difficult processes is machining. Just think about the problem of machining such an unusually shaped part of this size to a tolerance of ±0.010 inch – roughly the thickness of three sheets of paper. This required careful CAM programming of multi-axis milling machines, along with the development of special fixtures and cutting tools. Most of the first year was spent developing the CAM programs and refining the tooling and machining processes. A series of four multi-axis machines and machinists are now available to work around the clock, seven days/week as required to machine the NCSX winding forms. Finished winding forms are shipped to PPPL at a rate of about one per month.

The last step prior to shipment to PPPL is dimensional verification. This is performed on Major Tools' CMM machine shown on page 7. The data is analyzed using software that provides both a visual representation of the machining accuracy and statistical data. The "raw" data is also sent to PPPL and ORNL for analysis and acceptance review.

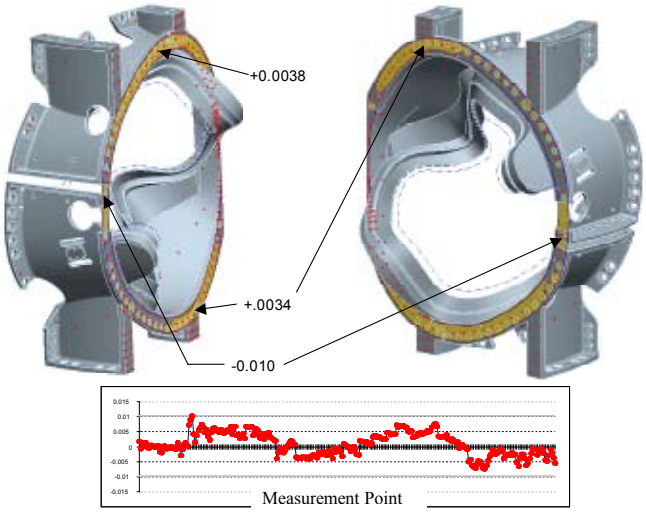




Major Tools uses a gantry-type CMM machine in the top photo. The left figure shows one form of output: a model of the casting with color contours representing deviations. The right figure shows the distribution of the deviations. ***(Figures courtesy EIO and Major Tools and Machine, Inc.)***



A "Point Cloud" overlaid on a CAD Model . Modern metrology methods, integrated with Computer Aided Design (CAD), permit the manufacturer to verify that the complex geometry of the parts produced meets dimensional requirements. The CMM measurements produce tables of data giving the 3-D coordinates in space. When these points are plotted on a computer, the myriad of points resemble a cloud-like image of the part—a "point cloud." Using CAD systems, the point cloud can be overlaid on the CAD model of the part to permit dimensional deviations to be determined.



PPPL and ORNL receive the "raw" dimensional data from EIO and Major Tool and Machine for pre-acceptance analysis and review, as shown in the illustration above. This data shows that the flange tolerances are within a band of +0.010 / - 0.008 inch. Most are within 0.005 inch.

PPPL Digest: Where else are these measurement techniques being used?

PH: They are used a lot in the automotive and aircraft industries. The German stellarator Wendelstein-7x also uses similar measurement techniques. These techniques are now spreading rapidly throughout industry as costs drop and as software improvements make their use easier.

PPPL Digest: What specific CMM techniques were used in the winding of the NCSX modular coils onto the winding forms?

PH: CMM measurements are absolutely essential to meet the ±0.020-inch tolerance for the current center positions for the modular coils. It took quite a bit "brainstorming" with PPPL and ORNL engineers and technicians and experimentation to arrive at the techniques that are successfully being used now. Originally we planned to shim each layer of turns of the winding. That technique was found to be very time-consuming and difficult, and the results were not satisfactory. The solution to this problem was to take advantage of what was previously viewed as an unfavorable characteristic of the stranded cable: its ability to be re-shaped by applying pressure. This characteristic allows us to wind the coil, measure turn positions, analyze the data, and then apply pressure to the coil via the blue clamp bars seen in the photo at the top of page 10 to re-shape the coil so the current center is within tolerance. However, it is also necessary to "band" the turns together to hold the coil shape after this operation. Fiberglass tape strips are periodically positioned between the turns during winding. These are used to band bundles of turns after they are pushed into proper position and shape. These bands assure that the coil maintains its shape after the temporary clamps are removed in preparation for epoxy vacuum-pressure impregnation.

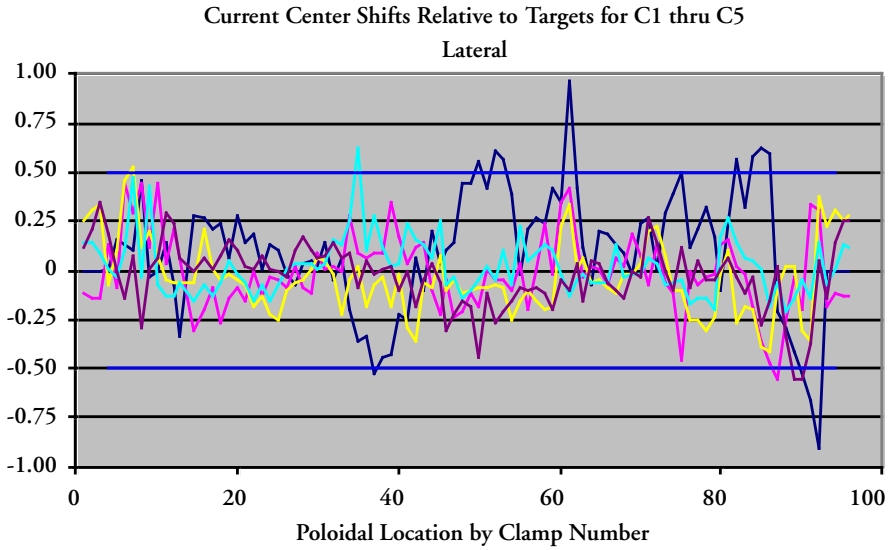
PPPL Digest: Suppose after winding a coil using this very sophisticated measurement technique, you found that the coil was out of compliance. What could you do to fix it?

PH: This is one of the major advantages of using finely stranded cable for the conductor. We can make corrections by applying pressure to reshape the cable conductor to get the coil current center to be within specifications. We routinely take advantage of this method of making corrections, especially when we know of an area where there is a deviation in the machining of the winding form. The most important thing is to keep the current center of the coil within its tolerance of ±0.020 inch. The individual conductors can be higher or lower, as long as the current center of the winding pack is where it should be.

PPPL Digest: How was PPPL staff trained in using these new techniques for winding the NCSX modular coils?

PH: We became aware of the state-of-the-art of metrology when sales representatives demonstrated its capability on small plastic stereo lithography

CMM measurements being performed in the NCSX coil winding area.



How did we do? Pretty well! The plots above show the current center vs. location for C1 through C5. The +/- 0.5 mm tolerance band is given by the blue horizontal lines. Only a few points exceed these limits. Analysis shows that these can be accepted.

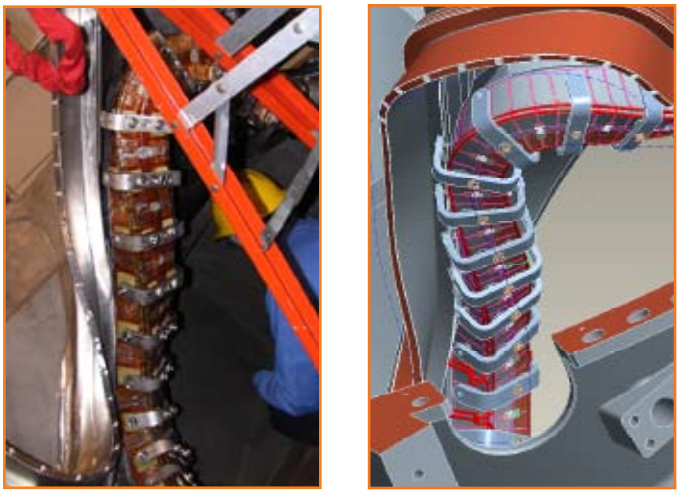
models of our parts. They demonstrated how a part could be scanned, "reverse engineered" (i.e., a computer model can be made of the part from the scanned data), and analyzing the data in a variety of ways. This convinced us that we could, indeed, measure these parts. This, in a way, was the start of our training. Steve Raftopoulos, who leads PPPL's metrology efforts, gained his proficiency through training courses given by the equipment manufacturers, but mostly through "hands on" self training, because of the uniqueness of our application. He then passed on his knowledge to our coil technicians where it is now used as an essential tool for winding the NCSX coils to the high accuracy required.

PPPL Digest: What is the current status of the modular coil fabrication?

PH: As of January, 2007, all 18 castings were produced, and 13 winding forms have been completely machined and delivered, representing all three kinds that are needed — types A, B, and C. So far eight coils have been wound and epoxy impregnated. Type C was the most challenging to wind (and machine) because it has the most pronounced curves.

PPPL Digest: Describe how the modular coils will be assembled on the NCSX vacuum vessel.

PH: The NCSX vacuum vessel is a highly-shaped twisted donut cut in three pieces. Each one-third segment of the machine (field-period assembly), consists of six modular coils and six toroidal field coils mounted around the one-third sector of the vacuum vessel. The coils will be carefully aligned to each other within an accuracy of ±0.020 inch, shimmed, and then bolted together. For assembly purposes, the coils are assembled in "three packs" consisting of one A, one B, and one C coil to permit assembly over the vacuum vessel (see the drawing on page 10). When the vacuum vessel was manufactured at the factory all of the ports were initially installed. Prior to shipment to PPPL, all but the mid-two were cut off each segment, leaving one-inch stubs. This will allow the coils to be carefully guided over the vessel. After the coils are in place, the vessel ports will be replaced and re-welded. PPPL's Mike Viola and our technicians have developed a clever and cost-effective method of using laser pointers to guide the three-dimensional crane motions necessary to bring the coils and vessel together. The final operation is to weld the three vessel segments together to

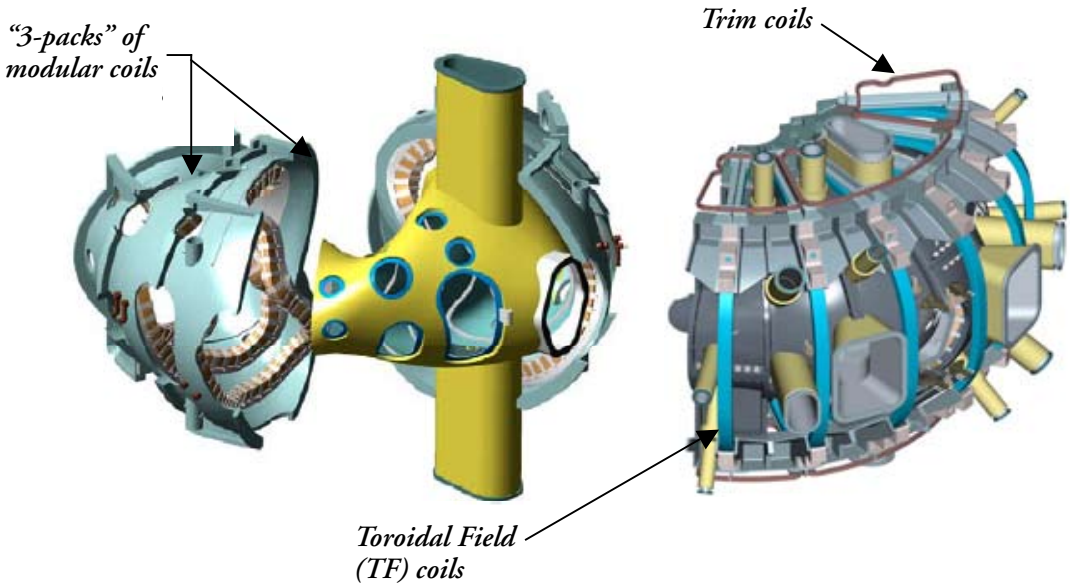


The photo on the left shows the fit-up between a casting and one of the completed modular coils during assembly trials. The photo on the right shows the CAD model.

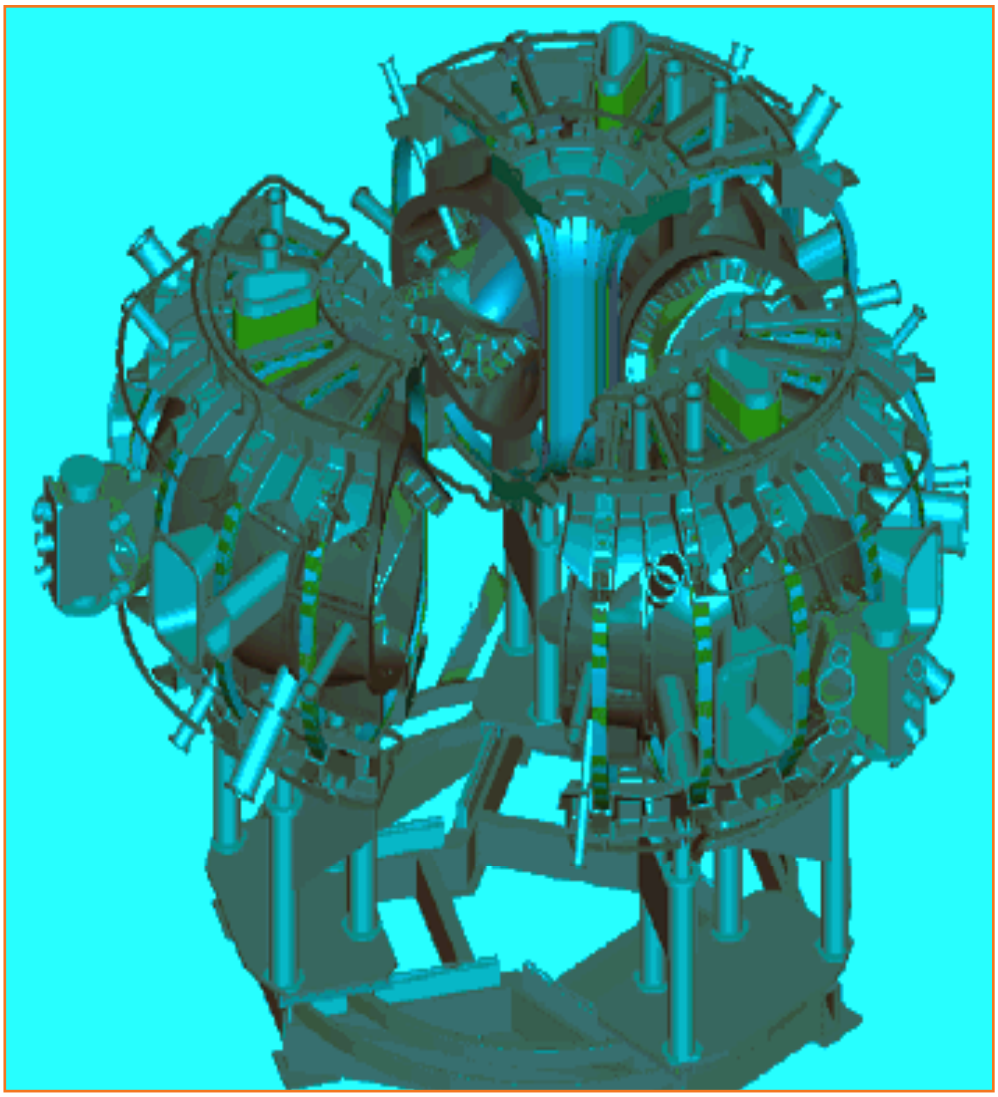
form the full vessel. The finished vessel will have about 100 ports when all three vessel segments are welded together. The precise assembly process is being developed now and will be tested with the actual coils on site. The mating of the coils and the vacuum vessel segments will be performed at PPPL. These field-period assemblies will then be moved to the NCSX Test Cell for final machine assembly.

PPPL Digest: What is the next step after the 18 modular coils and the other coils are mounted on the three vacuum vessel assemblies?

PH: The next step will be to assemble the resulting three field period sub-assemblies (i.e., one-third vacuum vessel segment with the associated coils joined to it) on the support structure at C-Site where the machine will be located in the NCSX



Coils meet vessel: The model on the right shows how two assembled "3-packs" of modular coils are brought together over the vacuum vessel. After these are aligned and bolted together, the toroidal field coils and trim coils are installed.



The structure permits the three machine segments to be pushed simultaneously so the vessel ends and spacers will engage properly.

Test Cell. This structure allows for the three machine segments to be simultaneously moved together. This simultaneous motion is necessary for the vessel segments to engage with each other. To complete the machine assembly, the three modular coil segments are aligned, shimmed, and joined together with bolts, the vessel segments are welded together from inside the vessel, and then the poloidal field coils are placed in position and mounted on their supports.

PPPL Digest: When will work on the support structure of the machine begin?

PH: The support structure design concepts were developed earlier, but were then put on hold to permit efforts to be concentrated on more critical components. Now that the work on critical components is well underway and proceeding well, work will resume later this year. Now the emphasis is on the field-period assemblies, which form the core of NCSX.

Phil Heitzenroeder joined PPPL in 1972 as an engineer in the Coil Branch. During his career at the Laboratory, he contributed to the engineering design of many of PPPL's fusion research devices and served in a number of management positions. He is presently the Head of the Mechanical Engineering Division. He received a B.S. degree in mechanical engineering from the New Jersey Institute of Technology in 1969. He is the recipient of the 2006 Kaul Prize for Excellence in Plasma Physics Research and Technology Development.

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