Work Remaining and Future Risks

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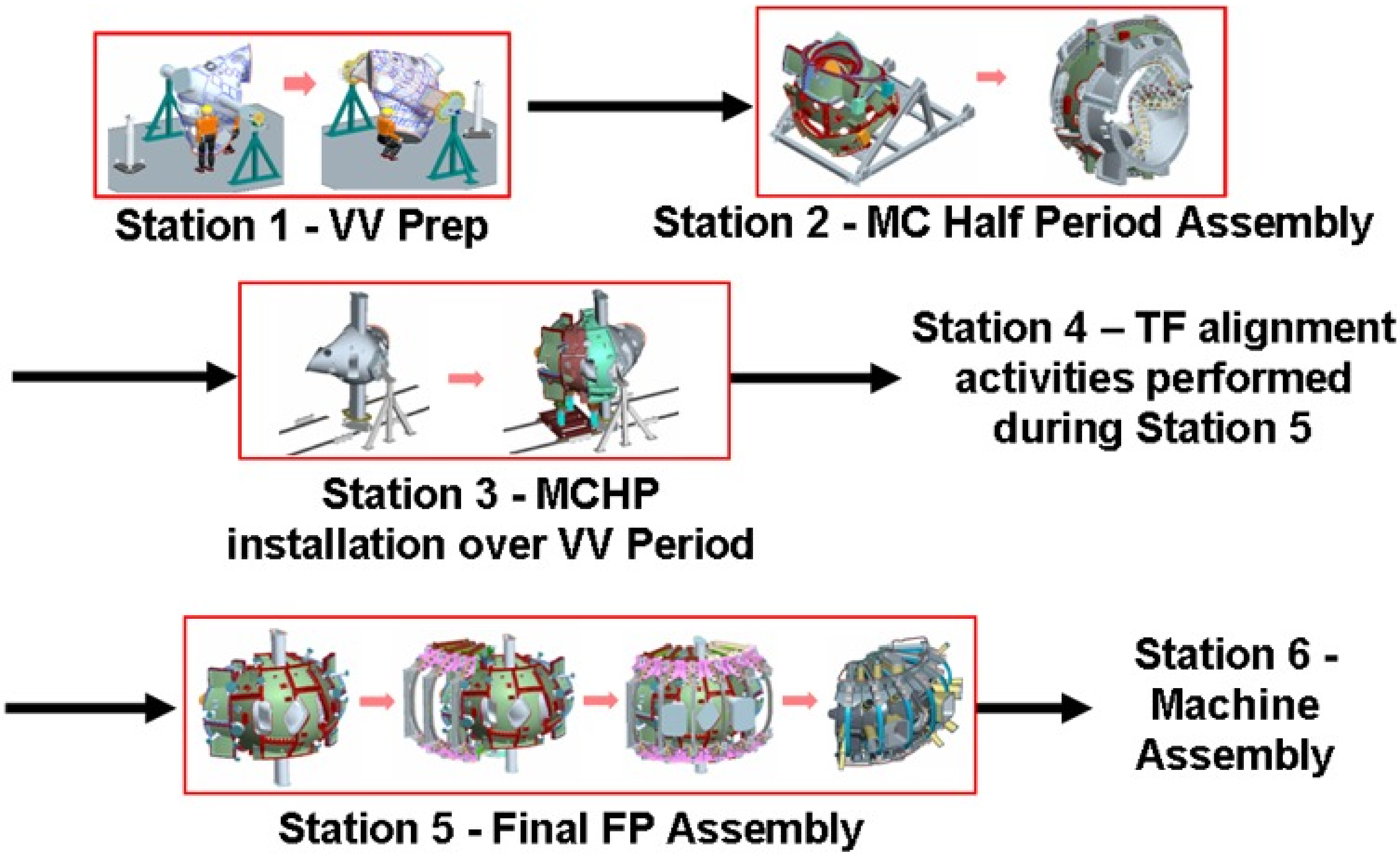
NCSX is starting field period assembly

- Design and fabrication risks for major components have been retired
  - All 3 VVSAs have been delivered
  - 16 of 18 winding forms have been delivered
  - 10 of 18 coils have been wound and epoxy impregnated
  - The 1st TF coil has been wound and epoxy impregnated
- Field period assembly is underway
  - Coolant tubes, heater tapes, thermocouples, and flux loops have been installed on the 1st VVSA
  - Assembly of the 2nd VVSA is in progress
  - Trial assemblies of the modular coils are being performed to develop assembly procedures and finalize the design of the modular coil interface hardware
- Final assembly will begin when the 1st field period is completed
- Integrated systems testing will follow

The bulk of work remaining and future risks are directly related to FPA and final assembly

- Field period assembly (FPA) and final assembly are the two largest cost elements and have the largest uncertainties
- Project engineering is the 3rd largest cost element and includes the "back office" support for FPA and final assembly
  - Metrology data analysis
  - Dimensional control
  - CAD support
- Other significant activities
  - Modular coil winding
  - TF/PF procurements
  - Electrical power

Field period assembly is performed in four separate stations

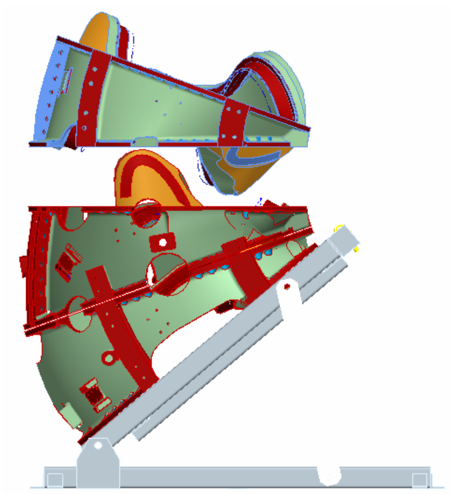


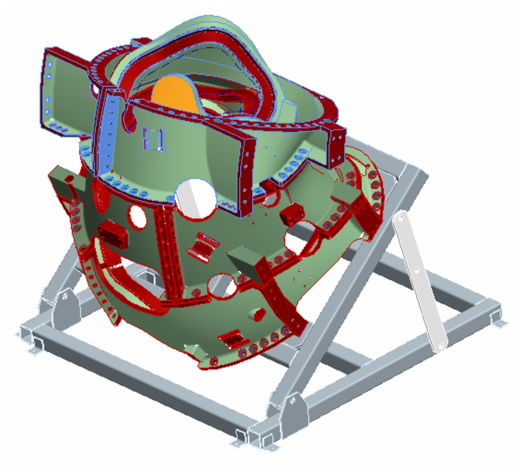
VV subassemblies are assembled in Station 1

- Verify geometry of VVSA and fit-up of ports
  - All 3 VVSAs have been scanned and port fit-ups checked
- Install coolant tubes, heater tapes, thermocouples, and flux loops
  - Installation procedures have been developed and optimized on the 1st VVSA
  - Work on the 2nd and 3rd VVSAs is progressing well
- Risk mitigation strategy was to start work as soon as possible on the first articles (production prototypes), work out assembly problems, and optimize assembly procedures off the critical path – worked very well

Modular coils are assembled in 3-packs on Station 2

- Dimensional control is critical
  - Winding centers for MCs need to be positioned within 60mils (1.5mm)
  - Tolerance is apportioned is thirds – 20 mils (0.5 mm) for winding the coil, 20 mils (0.5 mm) for assembling the coils into field periods, and 20 mils (0.5 mm) for assembling the field periods into a torus
  - Requires the use of state-of-the-art metrology equipment
    - CMMs used in coil winding provide 5mil (0.13 mm) accuracy
    - Laser trackers used in field period and final assembly for greater reach and improved accuracy (1.5 mils, 0.04 mm)
- Key elements for achieving dimensional control
  - Thinking ahead as to how the dimensional control requirements will be met, i.e. developing a dimensional control plan
  - Providing the right metrology equipment and software and the training needed to proficiently use these resources
  - Ample “back office” support processing and analyzing metrology data and integrating with Pro/E (CAD)
  - Developing, testing, and optimizing detailed assembly procedures

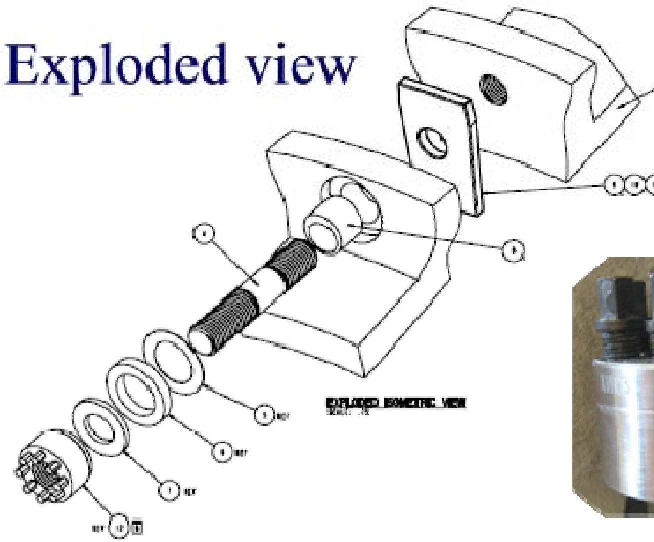




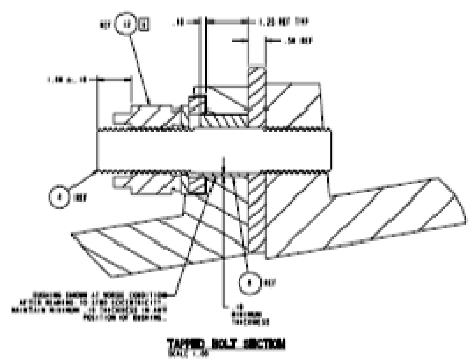
Coils are bolted together to form a structural shell

- Bolted joints use A286 1.375” (35mm) studs
- Supernuts are used to tension studs
- Studs are preloaded to 74 kips (329 kN)
- Shear is transmitted through alumina coated shims between flanges that provide high friction (mu~0.6)
- Shim thickness is selected to provide good coil alignment and fit-up

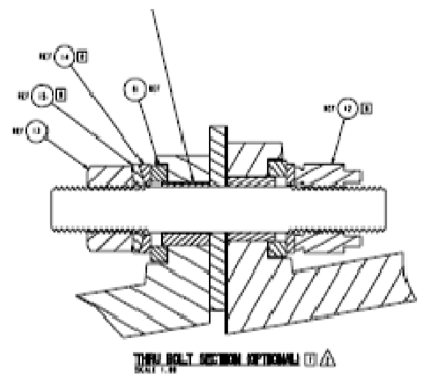
Exploded view



Supernut



Tapped hole

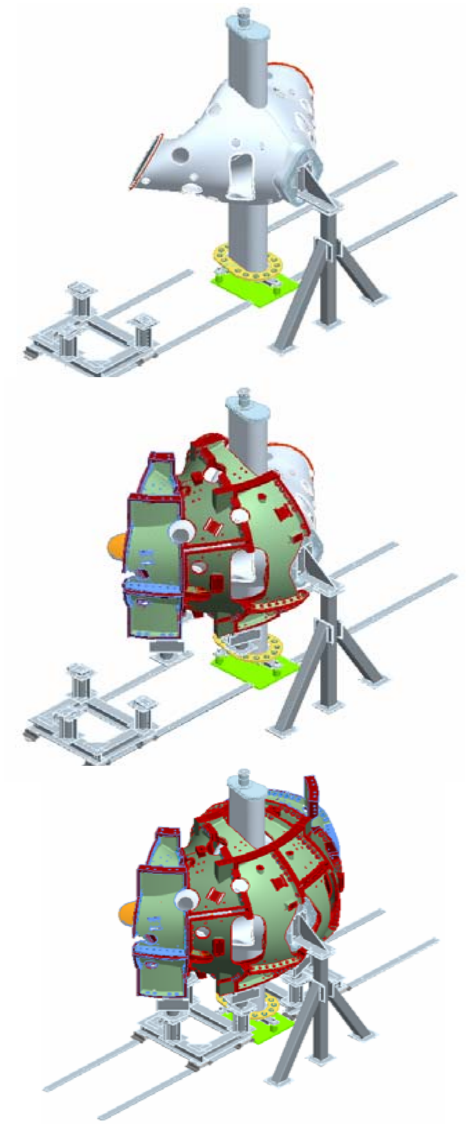


Through hole

Development trials on Station 2 are well underway

- Demonstrated the ability to fit-up the coils to the required positional accuracy using set screws for x-y control and shims for z-axis control
- Fit-up of the A1-A2 coils indicated that the gap between the aligned coils varied from 0.477” [12.1mm] to 0.531” [13.5mm]. The nominal gap size is 0.500” [12.7mm].
- Pressure sensitive film is being used to determined the table of shim thicknesses to provide adequate fit-up for the friction shims. A fit of better than 5 mils [0.13mm] appears to be required for adequate pressure uniformity.
- Design and fabrication of the inboard shims and procurement of the attaching hardware (studs, nuts, and washers) are the pacing items for the start of MC assembly on Station 2.

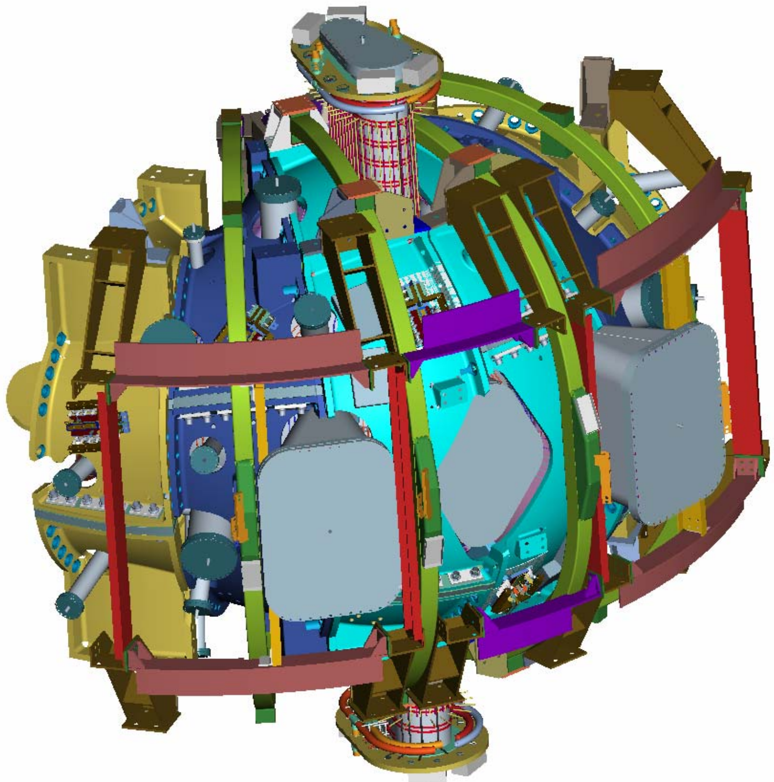
Modular coils are assembled over the vacuum vessel in Station 3



- The two MC half periods (3-packs) are “screwed” over the VVSA using the overhead crane with a 3-actuator positioner
- The trajectory is controlled by the operators following a map of points traced by laser beams on three screens
  – Technique demonstrated using a large concrete shield block and chain falls
- Once a half period has been manipulated over the VVSA, it is attached to a rail mounted positioner. Mating half-periods are pulled together and bolted.
- The VVSA is then hung from the modular coils.
- The completed assembly is then transported to the NCSX test cell

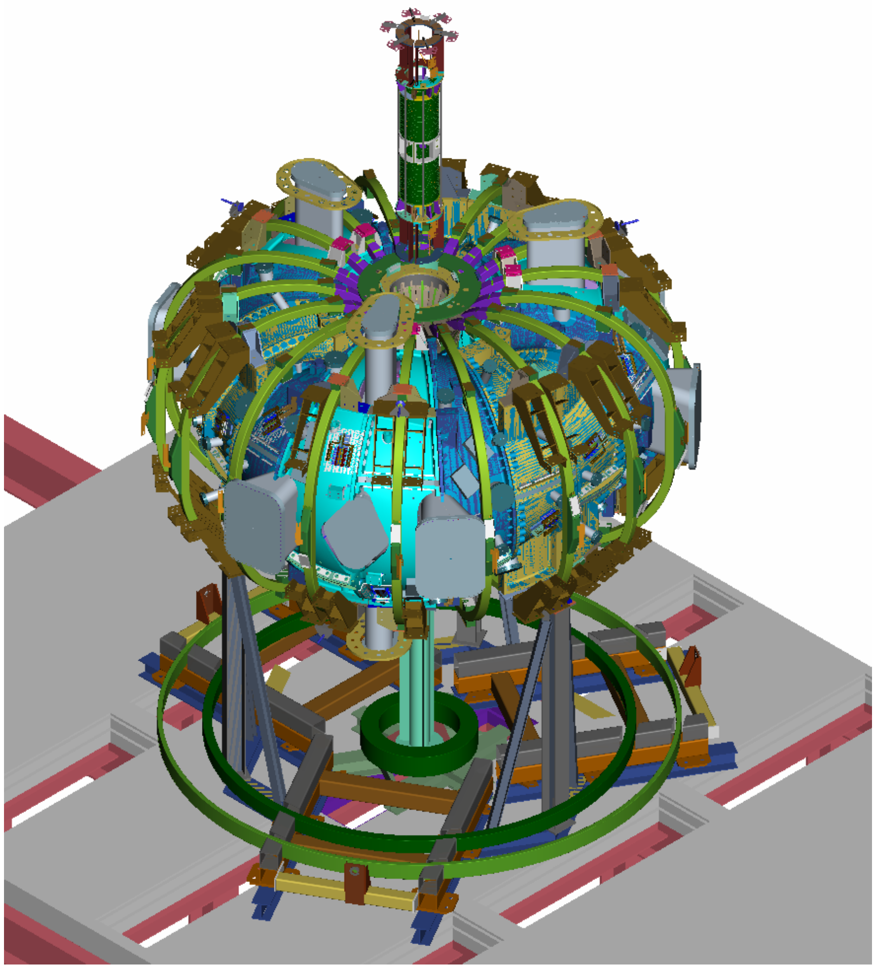
VV ports and TF coils are installed in Station 5

- Station 4 was eliminated by a change in the coil structures design
- All VV ports except the large Port 4s are installed prior to installing the TF coils for optimal access
- After the innermost TF coils are installed – the two centered on the Type A coils – the two Port 4s are tack welded into position
- The remaining four TF coils are then installed
  - TF coils must be aligned so that they lie in a radial plane with the noses wedged together
  - Tolerances on TF and PF coil alignment are twice as large as for the modular coils
- End TF coils are then removed so modular coil fit-up can be checked during final assembly
- PF coil support structures are installed after the TF coils



Completed field periods are mounted on sleds and moved together for final assembly

- Modular coils are fit with shims and bolted together
- Machine is then set on permanent supports and sleds removed
- The 3 VVSAs are welded together through spool pieces which are machined to precisely fill the gap
- TF coils are wedged together in the nose so centering forces can be reacted
- PF coils and the solenoid assembly are then installed
- The coils are tested at room temperature before the cryostat is installed
- The cryostat is installed followed by integrated systems testing, first plasma, and field line mapping



Future risks are mainly related to FPA and final assembly

- Proper alignment of coils when assembling 3-packs (Station 2), field periods (Station 3), and the full stellarator core (final assembly) is the most pervasive risk
  - Requires substantially more effort developing dimensional control plans, taking and processing measurements, and prototyping assembly operations than previously envisioned to properly manage these risks
  - Single largest factor contributing to cost and schedule growth
- Design of modular coil interface poses lingering technical and schedule risks
  - Development trials are still being performed to ascertain fit requirements for friction shims and fully characterize joint performance
  - Completion of the MC interface design is pacing the start of FPA operations on Station 2 (delivery of nuts, studs, and washers and fabrication of shims)

Future risks are mainly related to FPA and final assembly

- Substantial risks exist in other areas but these risks are not unfamiliar
  - Cost and schedule risks completing modular coil fabrications, e.g. punch list items
  - Cost and schedule risks completing TF and PF coil fabrication
  - Materials cost for future coil structures and base support structure porcurements
  - Other final assembly activities
    - Alignment of TF and PF coils
    - Final welding and leak checking of the vacuum vessel
- All jobs have been re-planned to include development activities needed to manage risks. Time and resources have been added to the baseline in recognition of the risks that exist.
- We look forward to your input on the completeness and reasonableness of these revised estimates