NCSX Construction Update

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Princeton Plasma Physics Laboratory
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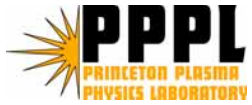


NCSX Construction is Making Excellent Progress

- Component production is going well.
  - Vacuum vessel completed.
  - 6 modular coils (of 18) completed through VPI.
- Earlier production start-up challenges were overcome.
  - Modular coil winding form vendor delays.
  - Modular coil winding learning curve.
- Physics requirements are being met.
  - Complex 3D geometries realized.
  - Field errors are minimized.
- Assembly activities are starting.

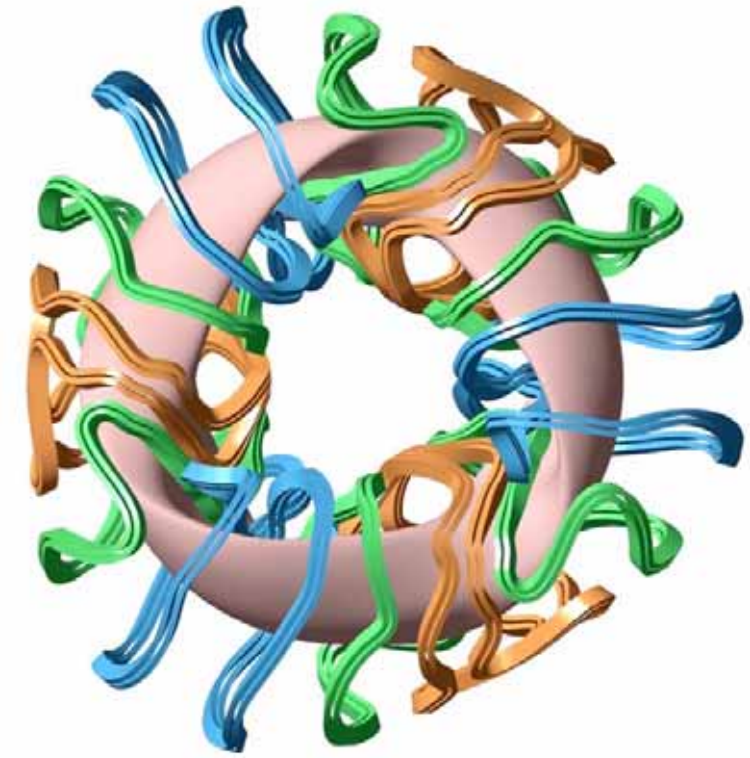
NCSX Optimized Configuration to Test High β, Quasi-axisymmetric Stellarator

Plasma Properties at β = 4%

- Quasi-axisymmetric. Low ripple.
  - Tokamak-like particle and flow behavior.
- Stable, good magnetic surfaces.
- Low R/⟨a⟩ (4.4)
- Reverse shear q-profile.
- 25% of transform from bootstrap.
- Constrained by engineering feasibility metrics.

Benefits

- Steady state without current drive.
- High-β, disruption-free operation.
- Compact, tokamak-like performance.



- 3-period plasma.
- 18 modular coils (3 shapes).
- TF, PF, & helical trim coils (not shown).

Mission:

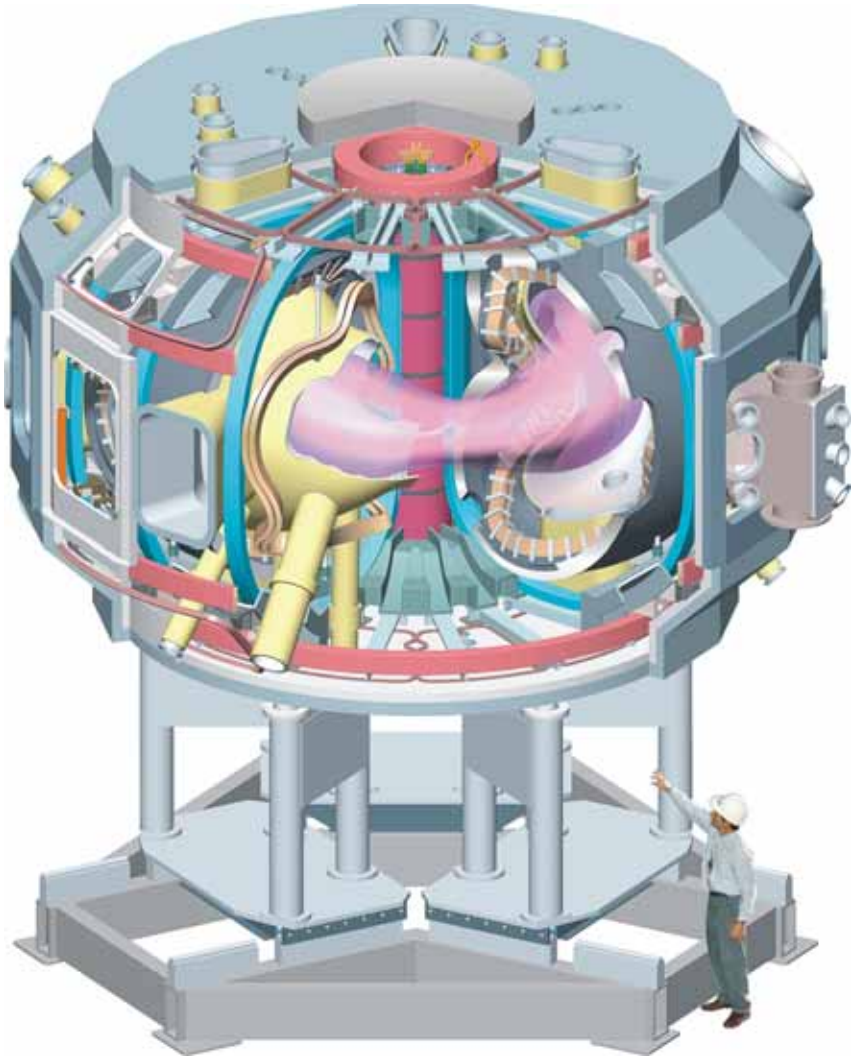
- Assess MFE attractiveness
- 3D toroidal plasma physics

Stellarator is Being Constructed to Mission Requirements

- R = 1.4 m, $\langle a \rangle$ = 0.3 m
- B = 1.2 - 2.0 T / pulse 0.5 – 2 s.
- Mod coil current center geometry as specified by optimization.
- Plasma configuration flexibility.
- Initial trim coil set.
- Field errors minimized (±1.5 mm coil accuracy, low μ, low eddy currents, stellarator symmetry)
- Diagnostic and heating port access.
- Embedded magnetic loops.
- VV bakeable to 350 C.

Acceptance Tests @ CD-4

- First Plasma @ B=0.5 T, I_P = 25 kA.
- e-beam mapping @ B= 0.1 T



Enormous Progress Since PAC-7 (July, 2004)

Status at PAC-7

- Completed Project Reviews needed for DOE construction approval.
- Awaiting proposals for winding form and vacuum vessel contracts.

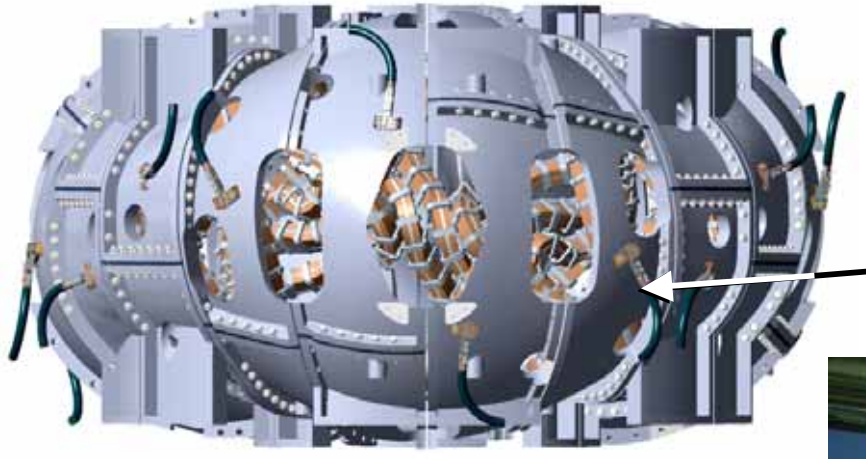
⇒ Received construction approval (CD-3) & placed contracts in Sept., 2004.

Since PAC-7, project has come a long way:

- Completed major manufacturing prototypes (MCWF, MC winding, VV).
- Completed vacuum vessel manufacture.
- Brought modular coils into routine production.
- Placed fixed price contract for TF coils.
- Developed field period assembly plans. Held international peer review.

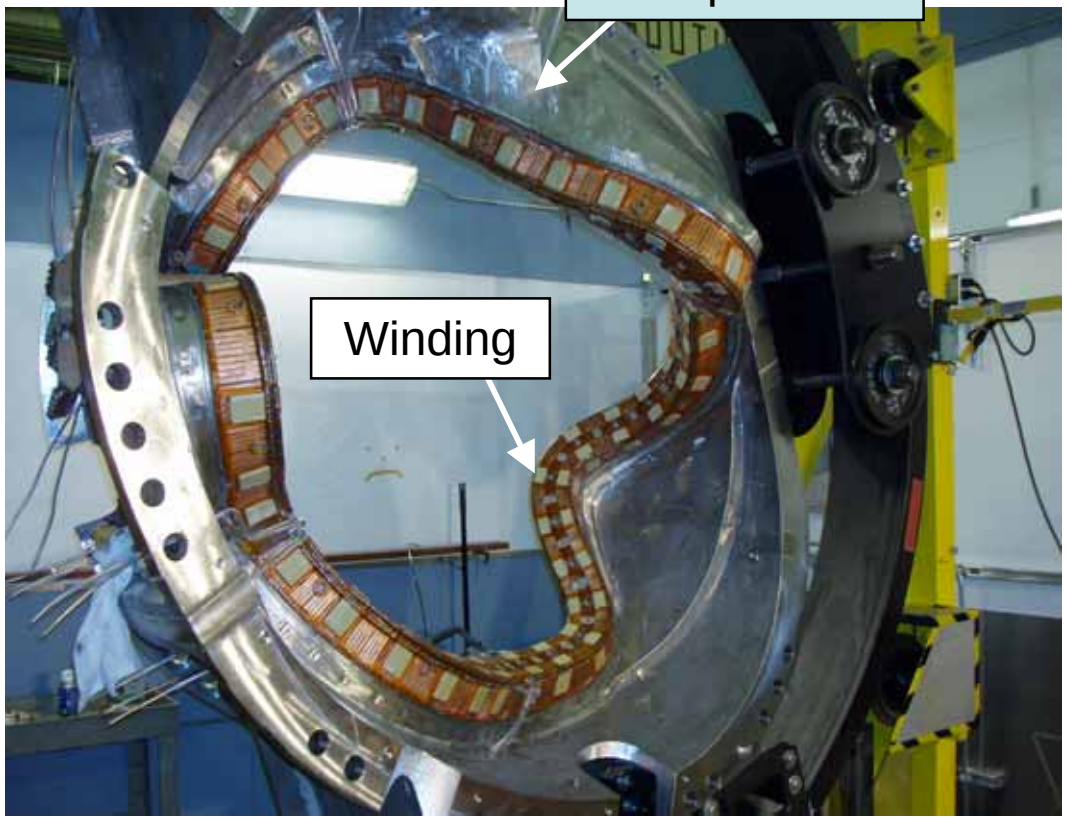
In moving from design, through R&D, and into production, significant challenges were successfully overcome.

Coil Design Reduces Field Error Risks



Modular Coil System

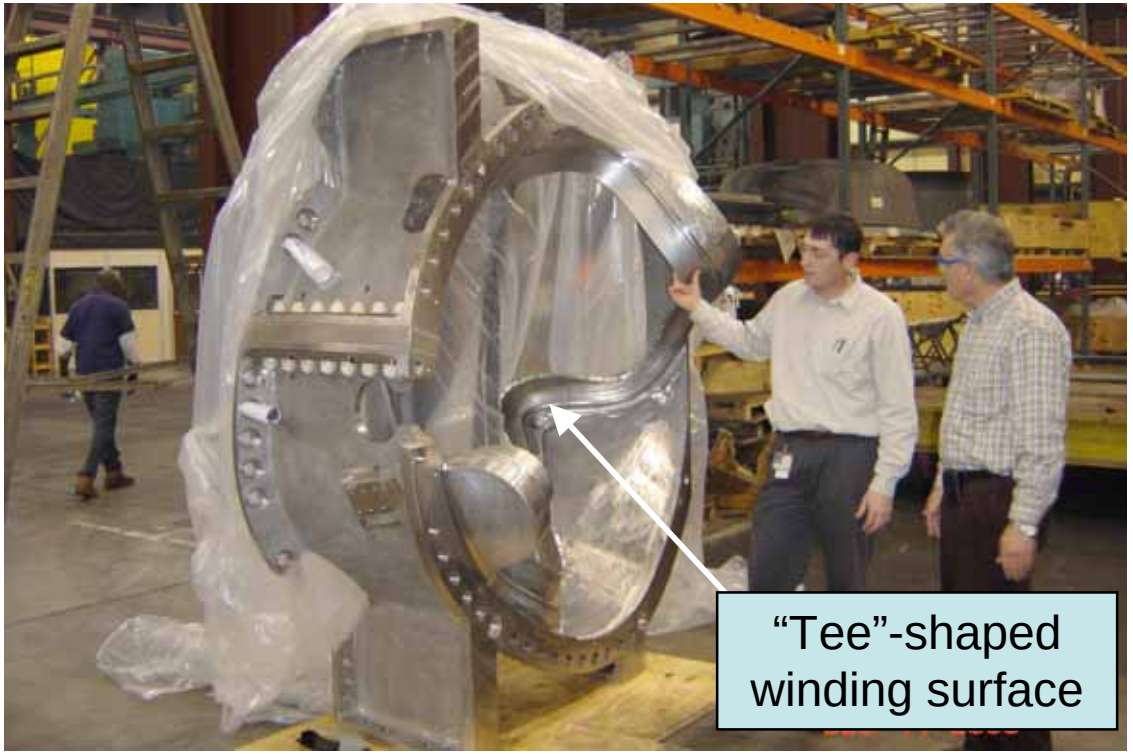
Modular coil winding form (MCWF) one per coil.



- Robust structural shell minimizes deflections.
- Toroidal and poloidal breaks inhibit eddy currents. $\tau \approx 17$ ms.
- Winding form stays with the coil as a permanent structure.
- Lead / crossover arrangement minimizes field errors.

Winding Forms Are Manufactured to ±0.25 mm Tolerance on Critical Surfaces

- Custom casting alloy (close to 316LN st. steel)
  - Low permeability ($\mu < 1.02\mu_0$)
  - Air quenchable (minimizes distortion risk).
- Optimized casting mold.
  - Hard wood pattern for part reproducibility.
  - Flow-solidification simulations used to design molten metal feed system.
- Machined on a series of multi-axis milling machines.



All 18 Have Been Cast
10 Have Completed Machining and Shipped to PPPL.

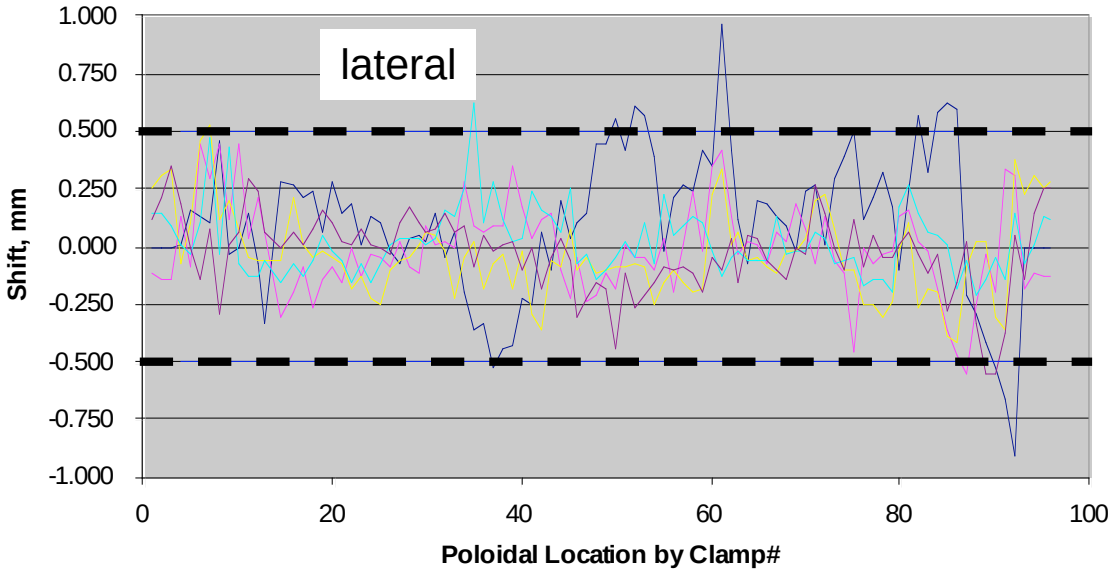
Winding Process Controls Current Center Position

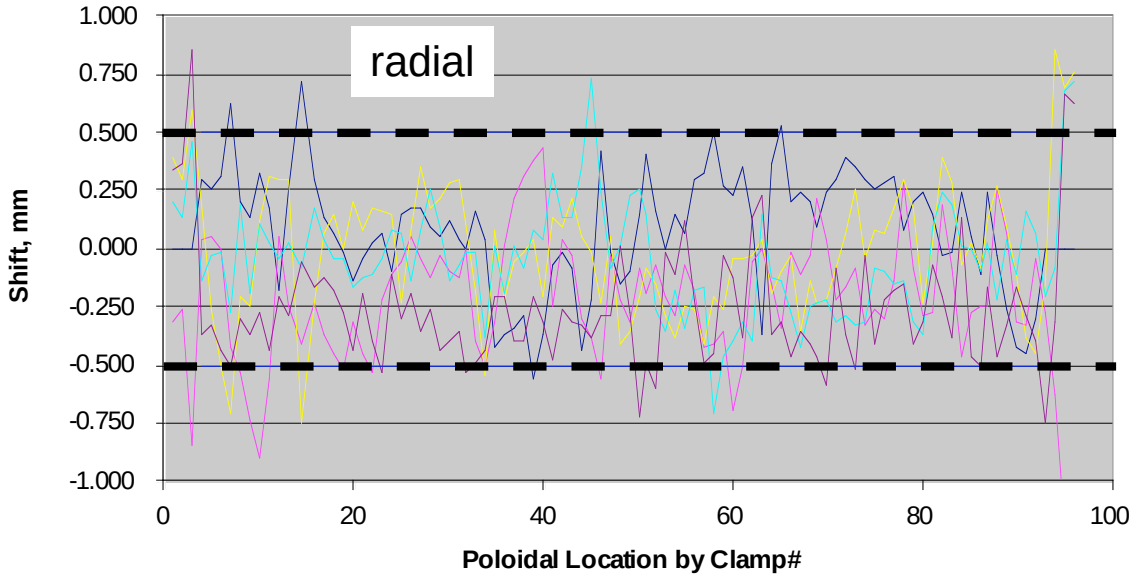
- Conductor is flexible copper “rope”.
  - Follows “Tee” winding surface.
  - Small (9x10 mm) conductor, wound 4-in-hand, maintains shape in bends.

- Winding pack dimensions are adjusted with clamps.
  - Compensates for winding form errors.
  - Bundle secured with fabric strips after adjustment.
  - Complete assembly is epoxy-impregnated by VPI.

Coil Construction Achieves ±0.5 mm Accuracy

Current Center Position Error (5 Type C Coils)



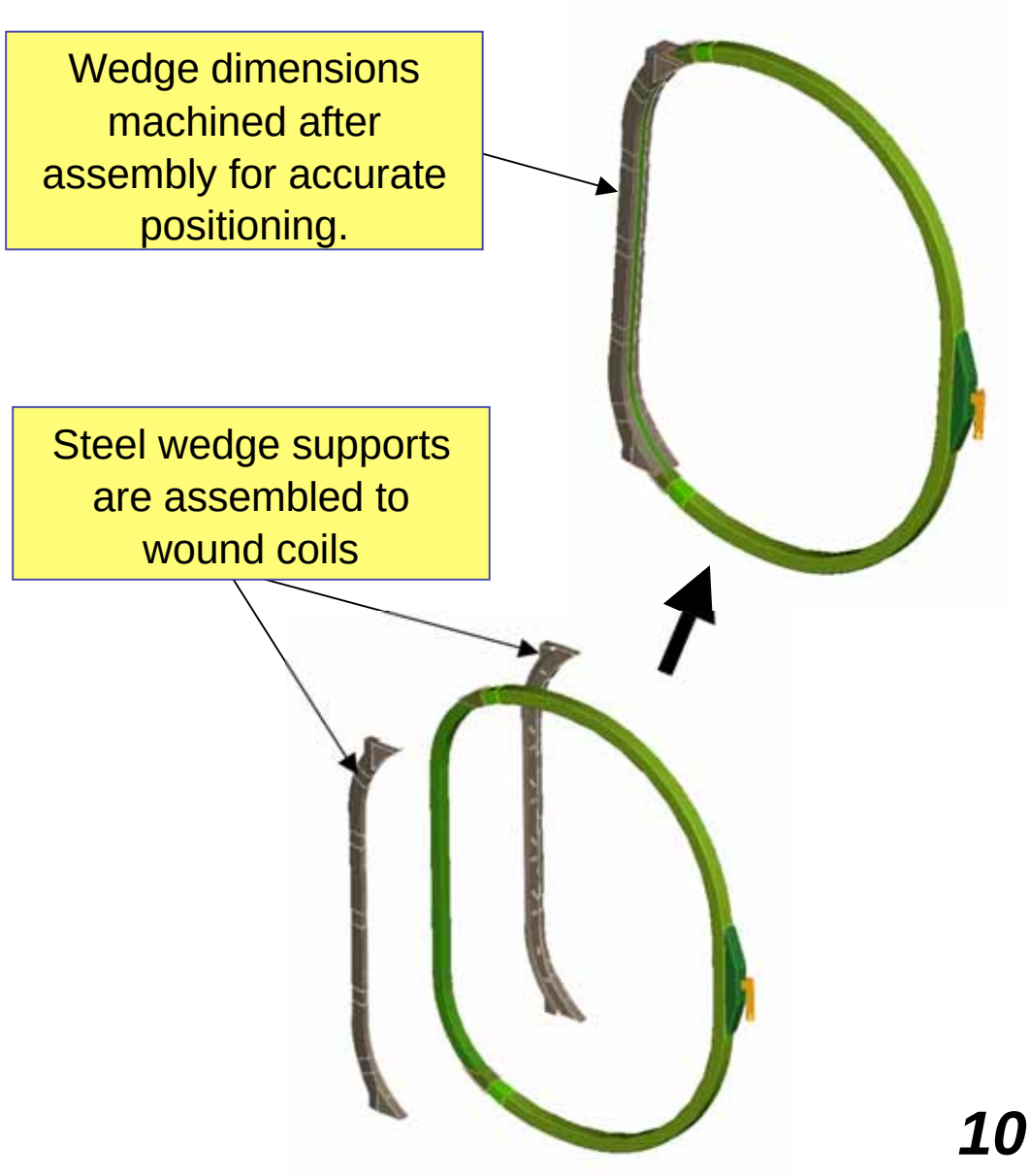


6 Coils Have Been Completed

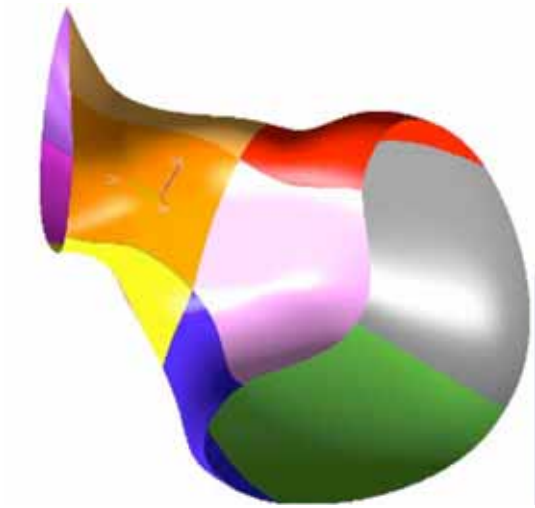
- First coil was successfully cooled down and tested at full current.
- All coils are tested at RT:
  - insulation strength
  - coil resistance
  - cooling line pressure.

TF Coil Construction Ensures Accurate Positioning

- TF contract was awarded to Everson Tesla, Inc. (U.S.) in May.
- Their winding line has been constructed and is being tested.
  - Winding will start in November.
- They have a lower-tier subcontract in place to supply the wedge supports.
- First coil will be delivered in February.



Large-Panel Vacuum Vessel Construction Achieved ±5 mm Accuracy



Material: inconel
Low μ (< $1.02\mu_0$),
Low eddy currents ($\tau \approx 3$ ms)

Segmentation Plan
(10 per Half Period)
Minimizes Welding
& Distortion Risk

Panels Pressed at Room Temp.
Assembled & welded on skeletal fixtures

All 3 Field Period Sectors Completed!

Assembly Activities Have Started

Mounting locations for flux loops and heating/cooling hoses are transferred from CAD model to vessel using laser scanner.

Most of the Project Risks Identified in 2004 Are Now Retired

Vacuum Vessel- uncertainties in manufacturing cost and schedule.

- Basic process (large panels, full penetration welds, fixturing, inspection) was demonstrated on prototype 20-degree sector, prior to production.
  - Lesson learned from ATF experience in 1980's.
- Full vessel was completed without significant technical problems.
- Delay (~9 months) was accommodated by float in the schedule.

Modular Coil Winding Forms- cost and schedule uncertainties.

- Alloy and casting process were developed via prototype prior to production. All 18 castings were completed with high quality and no significant issues.
- We did not prototype machining, so efficient process had to be developed on first 3 production winding forms, causing ~6 month delay.
  - Project and vendor worked cooperatively to find optimum solution.
  - Vendor has delivered ~1 per month since February.
- Delay was accommodated by schedule float and assembly re-planning.

Project Risk Management- Continued

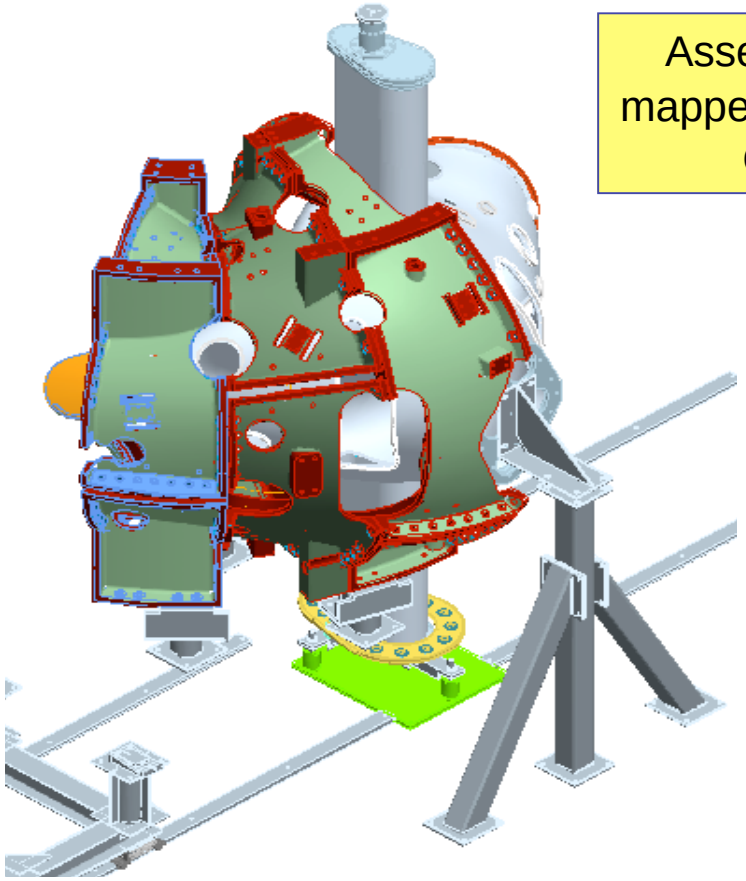
Modular Coil Winding: demanding requirements met.

- Cost-effective dimensional control process was developed on “twisted racetrack” R&D coil in 2005.
  - Post-winding repositioning strategy replaced original (inter-turn shimming) plan. Three-way win: better results, lower cost, more margin!
- Insulation weakness (~2 MΩ to ground) on first coil was corrected by minor design change and relatively easy repair. Coils now testing @ >100 GΩ.
- Process developed on twisted racetrack has been technically successful in production.
  - Cost efficiency and production rate are steadily improving.

Main remaining risks- assembly operations- are being managed.

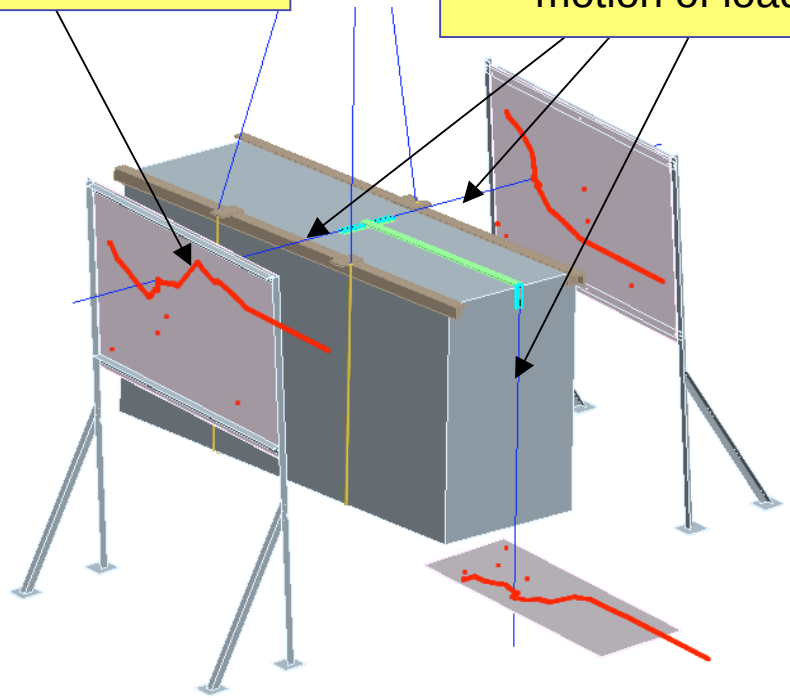
- Process uncertainties have narrowed considerably as a result of design and R&D work since 2004.
- Recent review (reviewers from W–7X, HSX, SNS) provided valuable input.
- We are prototyping procedures on Field Period #1 while assembly is still well off the critical path.

Next Step: Build Field-Period Subassemblies



Assembly trajectory mapped to 2D traces via CAD model

3 laser beams track traces to guide motion of load

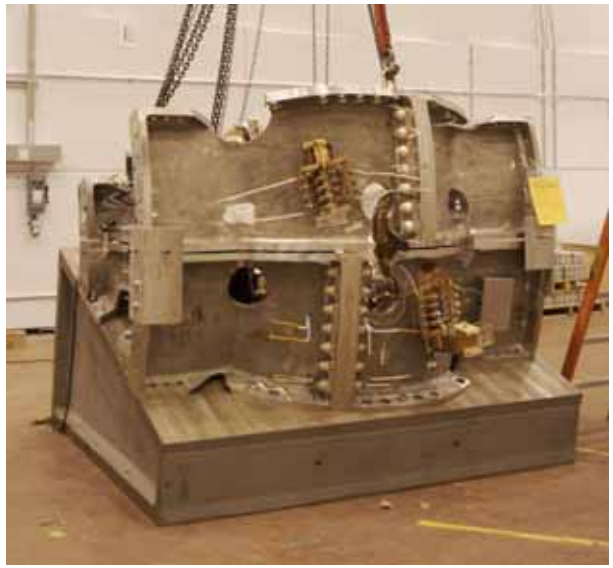


Modular Coil triplets will be installed over vacuum vessel.

- Coils are moved along assembly trajectory suspended from crane.

Low-cost trajectory-following technique was successfully demonstrated.

Coil-to-Coil Fit-Up Tests Have Started

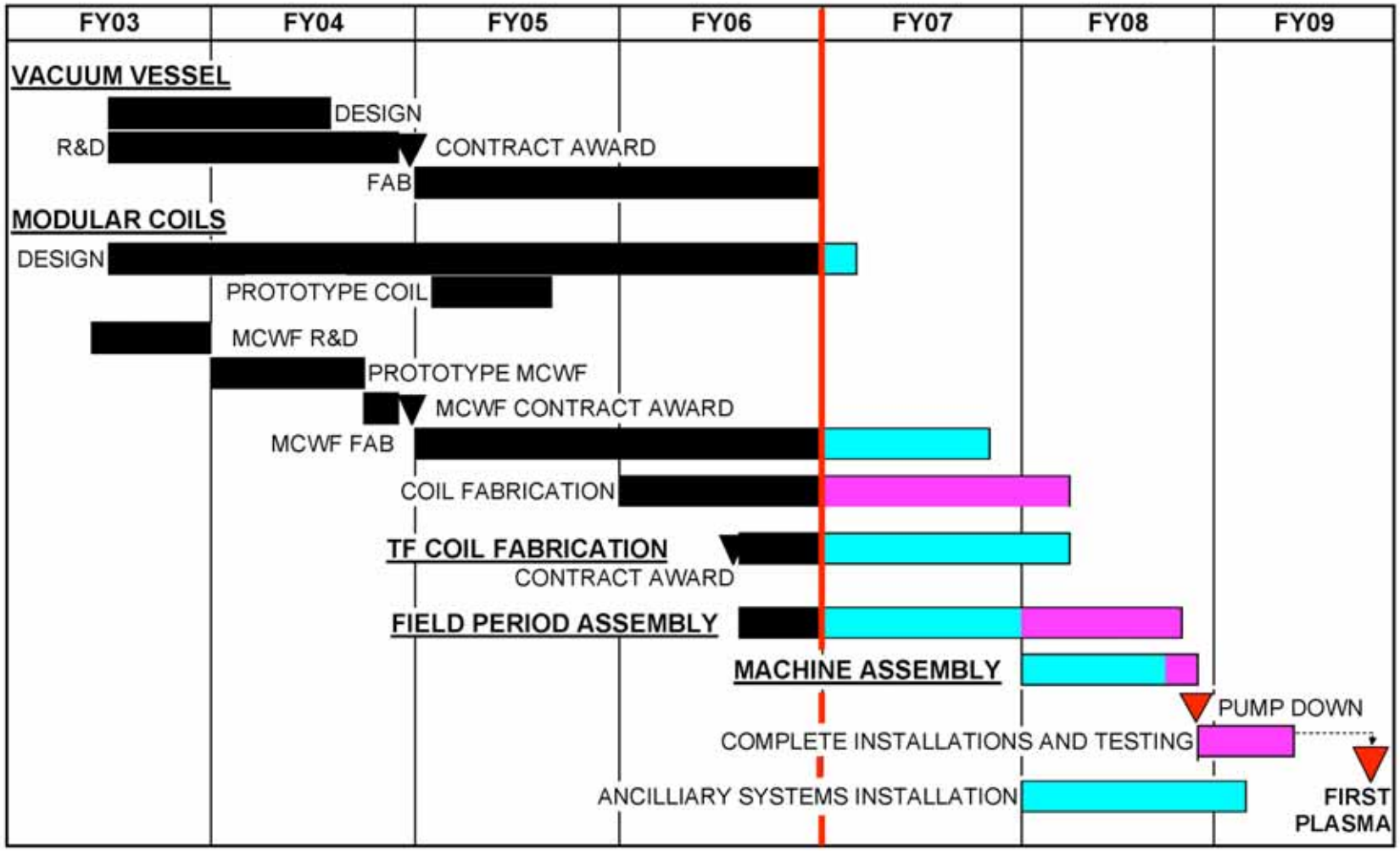


- Test handling and metrology procedures.
- Resolve issues while assembly activities are well off the critical path.

Availability of All MCWF Types Permits Fit-Up Trials Prior to Winding

Fit-up of a Type C coil and Type B winding form

NCSX is On Schedule for July, 2009 First Plasma



Construction Project Budget: $92.4M

- Scope is being managed with a tight focus on CD-4 objectives.

ECH First Plasma Scenario is Being Investigated

Replace 25 kA Ohmic First Plasma Scenario with Currentless ECH Scenario?

- Available hardware at ORNL & PPPL offers several Day-1 ECH possibilities:

Source	Frequency/ harmonic #	Resonant field (T)	Critical density $x10^{12}$ cm^{-3}	Day-1 Power (kW)
28 GHz gyrotron	28 GHz / fund	1	**9.2**	**40 kW**
	28 GHz / 2nd	**0.5**		
	15.3 GHz/fund	0.546	2.7	15 kW
18 GHz klystrons	18 GHz / fund.	0.64	3.8	20-30 kW

- Standalone gyrotron system at ORNL could produce 40 kW, 500-ms pulse.
  - HV power supply, magnet, socket, controls, window cooling system.
  - ATF launcher can be used to provide focussed power.
- 15.3 GHz operation of 28-GHz gyrotron is being tested at ORNL.
- Possible ECH costs: transportation, installation at PPPL, launcher mods.
- Offsetting savings:
  - Reduce number of coil circuits from 4 to 2 (power modular coils only).
  - Some power supplies and PF coils could be deferred until later.

Standalone Gyrotron System Includes HV Power Supply, Socket, Magnet, Water Manifold

4’x6’ footprint

- Controls, magnet, and waveguide are compatible with 200-kW upgrade at 28 GHz using existing PPPL supplies.

ECH First Plasma Scenario May Be More Attractive

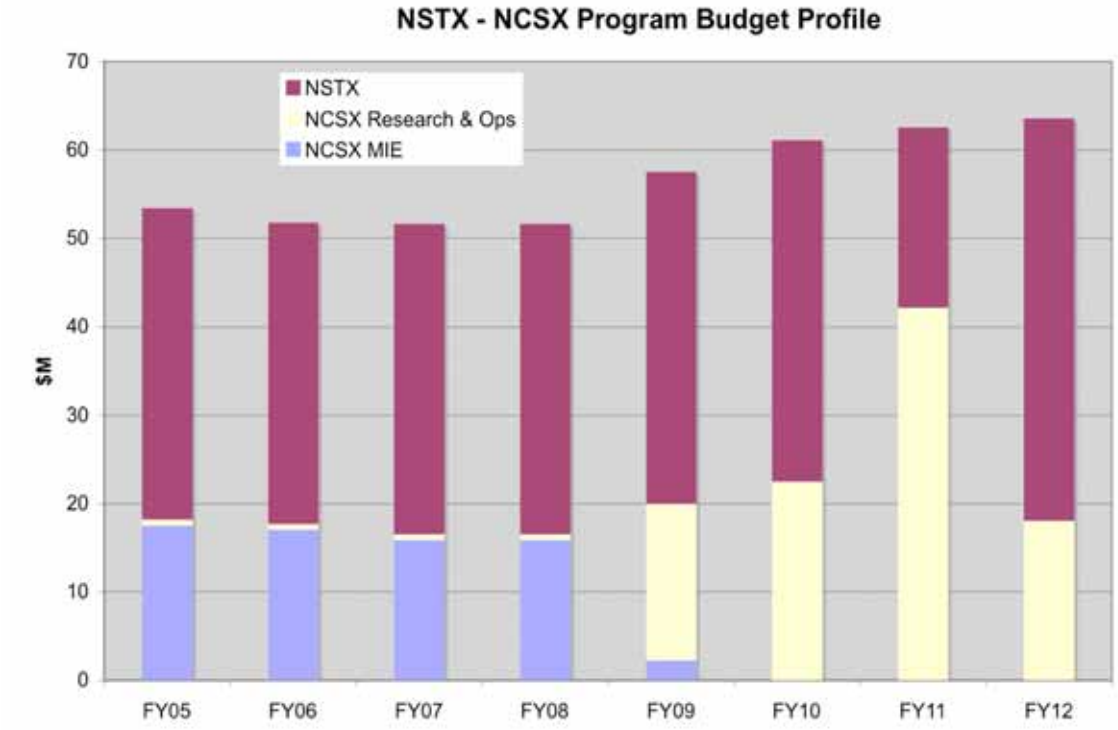
- Demonstrates currentless NCSX startup option.
  - Simpler plasma control (avoiding Ohmic currents) may be advantageous for initial operations.
  - Note: ECH is now part of NCSX program plans for FY–11 and beyond (MZ).
- Cost Assessment (preliminary): ECH First Plasma option appears promising.
  - Will complete evaluation this month in preparation for Lehman Review.

Change would affect First Plasma definition- requires DOE approval.

We will make recommendation to DOE at NCSX Lehman Review (Dec. 19-20).

PAC advice is requested.

Research Planning is Consistent With SC's Five-Year Plan (FY07-11)



National NSTX-NCSX budgets.

As presented to OFES in March, 2005 as input to 5–Year Plan

- Combined NSTX+NCSX national budget assumed to be essentially flat.
- NCSX and NCSX will operate in alternate years.
  - Current NCSX plan: 6 weeks in FY-09, 24 weeks in FY-11.
- NCSX currently focused on construction. Small research prep effort.
- Funding for NCSX diagnostics and facility upgrades starts in FY-09.
  - Planning is under way now. PAC input requested.

Summary

- Stellarator is being constructed to mission requirements.
- Major components are in production– several finished.
- Assembly activities have begun.
- Most of the construction risks are behind us.
  - Remaining risks are actively managed.
- On schedule for July, 2009 First Plasma.
- Research program planning is under way.