Engineering Design of the NCSX

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43rd Annual Meeting

APS Division of Plasma Physics

Long Beach, CA

October 29, 2001

Abstract

A new facility, the National Compact Stellarator Experiment (NCSX), is being designed to support experimental research on the physics of high-beta, low aspect-ratio stellarators, using the quasi-axisymmetric stellarator (QAS) concept to merge tokamak and stellarator physics. The design is based on a 3-period QAS plasma configuration with an aspect ratio $R/\langle a \rangle = 4.4$, a major radius R = 1.4 m, and 3D shaping to provide desired physics properties. About one-fourth of the rotational transform is provided by the bootstrap current, the remainder by coils. A coil system consisting of modular, toroidal, poloidal, and trim coils provides required physics properties, flexibility (including Ohmic startup), and magnetic fields up to at least 2 T on axis. The plasma is surrounded by a conformal vacuum vessel that has an internal structure to support carbon plasma facing components that are bakable to 350 C, and ports for heating, pumping, diagnostics, and maintenance access. The design accommodates up to 12 MW of plasma heating--6 MW of neutral beams and 6 MW of radiofrequency waves.

The NCSX is Designed to Meet Physics Requirements

Plasma parameters

- R = 1.4 m
- B = 1.7 T (reference configuration); ≥2 T in reduced-iota configuration.
- I_P = 175 kA (reference configuration)
- Design implications of higher B and I_P are being studied.
- Physics properties (targeting LI-383 β=4% reference plasma):
  - Internal and external iota, aspect ratio
  - Stability, confinement, and surface quality.

Coils

- Produce reference plasma parameters and physics properties.
- Produce reference 1.7-T pulse scenario:
  - Inductively initiate on vacuum surfaces.
  - Ohmic pre-heat and fast inductive current ramp (3 MA/s).
  - Flattop for 0.3 s to heat to high beta and hold for 0.2 s.
- Provide flexibility in internal iota, external iota, shear, beta limit, quasi-symmetry, profile shapes.

NCSX Physics Requirements, continued

Plasma facing components

- Long connection lengths (≥120 m).
- Poloidal limiters with minimal coverage initially.
- Reconfigurable, with provision for future divertor hardware:
  - plates for heat removal (12 MW / 1 s) with minimum impurity generation.
  - baffles and pumps for neutrals control.
- Carbon-based materials (e.g., graphite or CFC) bakable to 350 C.
- Coverage expandable to 100%.
- Electrically biasable regions.
- Accommodate plasma beta and iota flexibility.
- Protect vacuum vessel and in-vessel hardware.

Vacuum and wall conditioning

- Base pressure 2×10^{-8} torr (5×10^{-9} torr for impurities).
- Bakeout of carbon PFCs to 350 C with vessel at 150 C.
- Glow discharge cleaning at bakeout temperatures or between shots.
- Boronization, lithiumization (upgrade).

NCSX Physics Requirements, continued

Heating

- Neutral Beam Injection: 6 MW (3 MW initially)
  - 4 PBX-M beamlines (1.5 MW per beam, E = 50 keV).
  - Balanced tangential injection: 2 co- / 2 counter (1 co- / 1 counter initially).
  - Pulse length 0.3 s (upgradable to 1.2 s)
- Ion Cyclotron Heating: 6 MW upgrade.
  - Inboard-launch mode conversion scenario @ 20-30 MHz using available system.
  - 3 launchers at bullet cross section
  - Pulse length 1.2 s.
- Port space for alternate NBI arrangements, high-frequency fast wave ICH, or ECH.

Fueling

- Gas injection: programmable, with density feedback.
- Pellet injection upgrade: multi-shot; inside-launch via pre-installed guide tubes.

NCSX Physics Requirements, continued

Electromagnetics

- Vacuum vessel time constant <10 ms to avoid kink-mode stabilization.
- Loop voltage and vertical field penetration time constants short enough to maintain adequate magnetic surface quality.
- Be able to withstand EM forces due to disruptions (plasma disappearance).

Operation

- Design life: 10 years.
- Pulse intervals: short pulse <5 min.; long pulse <15 min.
- Number of pulses: 100/day, 13,000/year, 130,000 lifetime.
- Fuel: H, D
- D operation administratively limited to be compatible w/existing shielding.

Engineering Solutions

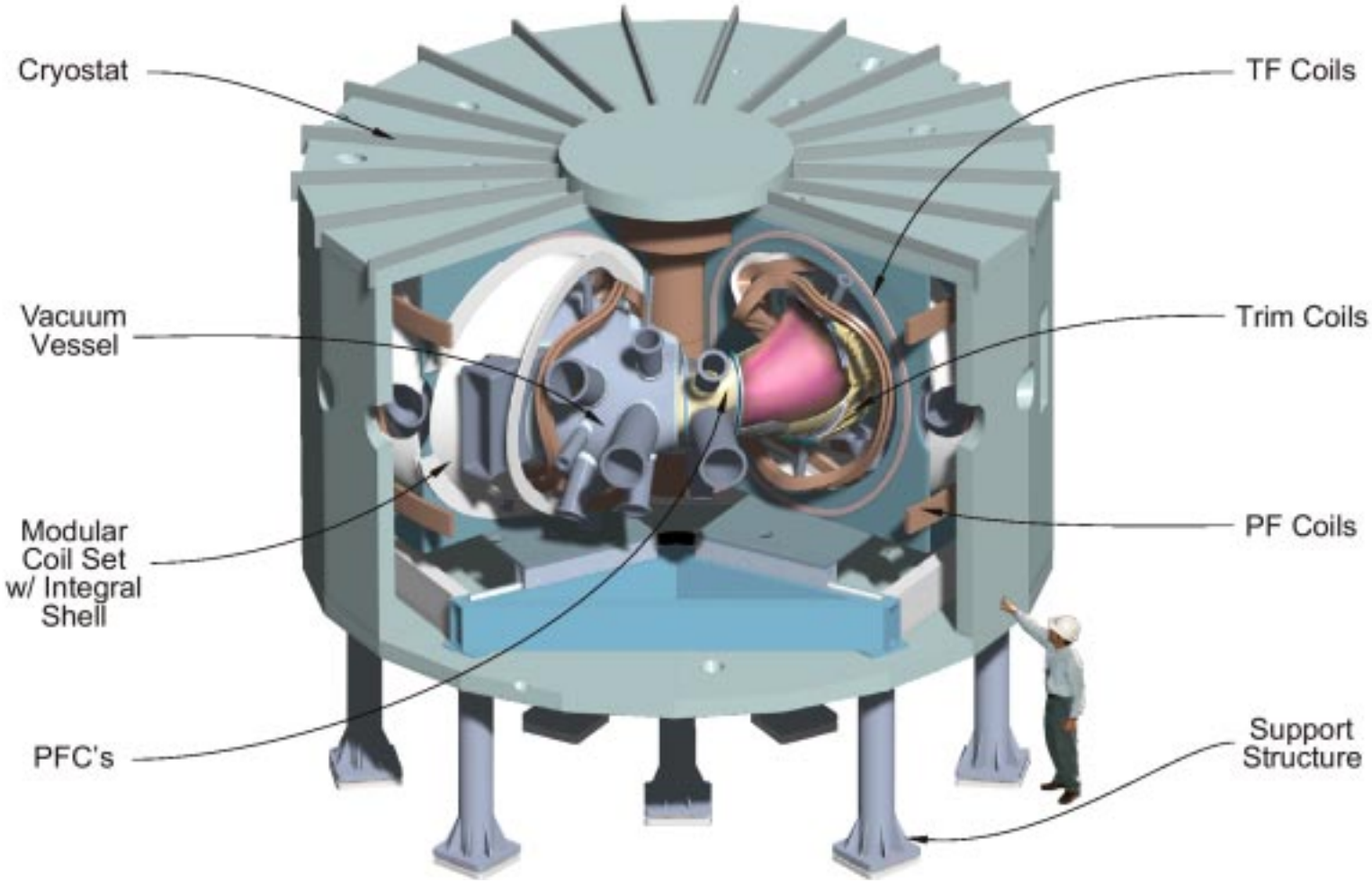
Coils

- Modular coils: new design with 18 coils (3 types)
  - no coils on symmetry planes for optimum access.
  - electrically grouped (by type) into 3 independent circuits for flexibility.
- TF coils: 18 planar coils, centered on modulars for optimum access.
- PF coils: 5 pairs (2 for OH, 3 for EF).
- Above coils use flexible copper conductor wound on accurate structural supports. Operate at cryogenic temperatures.
- Trim coils: m=5 and m=6, inboard and outboard at bean cross section.

Vacuum vessel and PFCs

- Conformal inconel vacuum vessel (formed or cast)
  - Provides high vacuum conditions
  - Supports in-vessel hardware (e.g., PFCs, trim coils, RF launchers)
  - Provides diagnostic access based on physics program needs.
- Conformal first wall made from large carbon-based panels
  - Mounted on in-vessel support ribs for convenient reconfigurability.

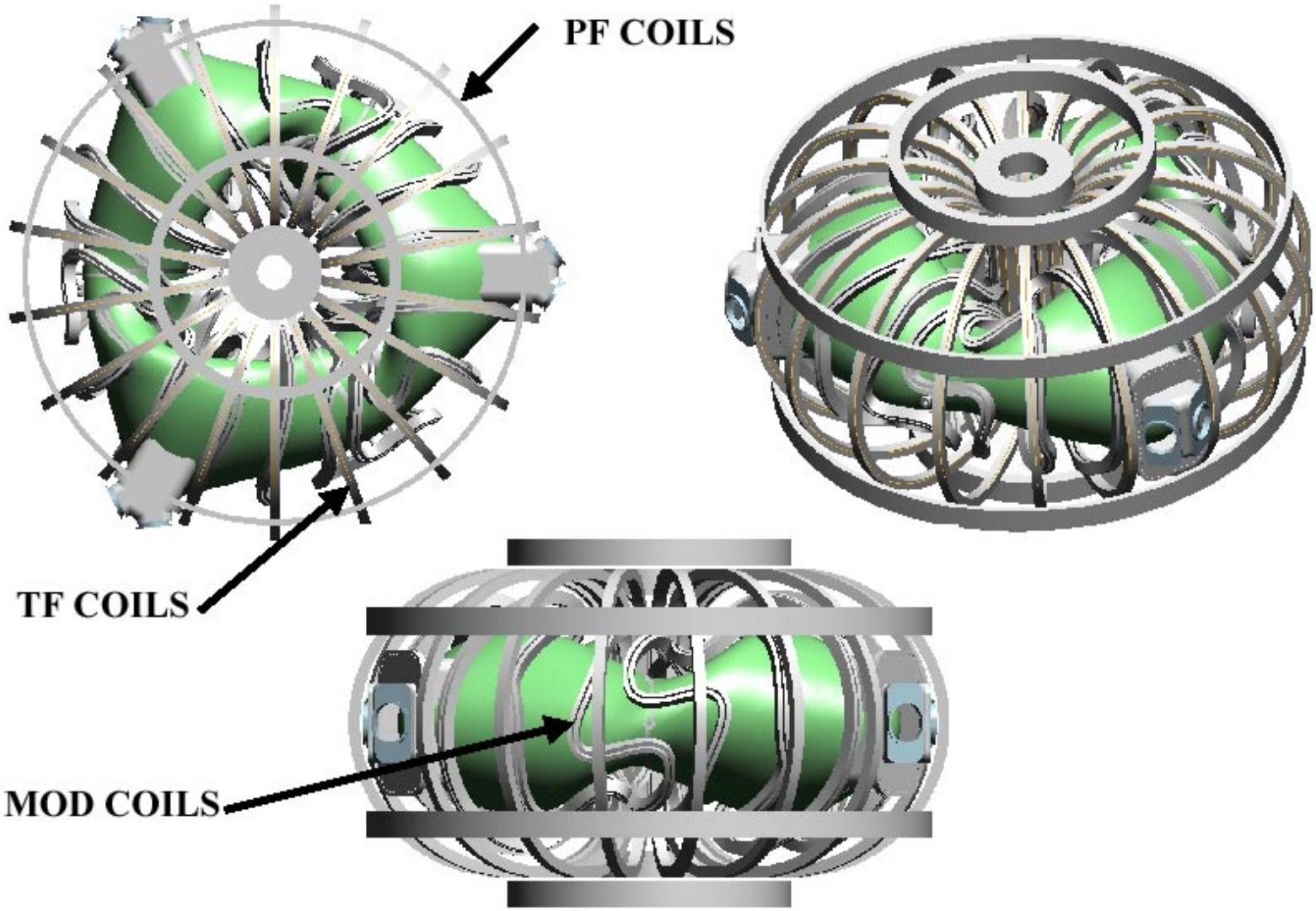
NCSX Stellarator Core Concept



Sited at PPPL; uses existing ancillary equipment and infrastructure.

Project cost ~$69M (Oct., 2002 - March, 2007).

Vacuum Vessel and Coils



Modular coil requirements

- **Meet performance requirements**
  - **1.7 T scenario with 0.46s flattop**
  - **2.0 T with reduced external iota**
  - **15 minute rep rate (5 minute rep rate for short pulse)**

- **Provide flexibility**
  - **Independent control of modular and PF coils provided**
  - **Variable background TF field**

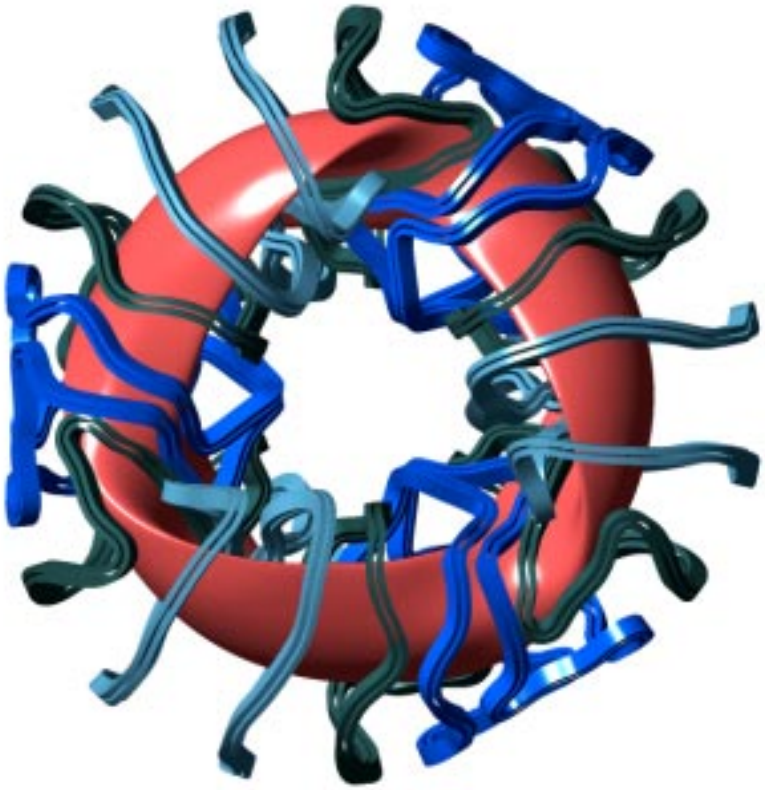
- **+/- 1.5 mm assumed for winding accuracy**

- **Coils must provide access for tangential NBI, RF, vacuum pumping, diagnostics, and personnel access**

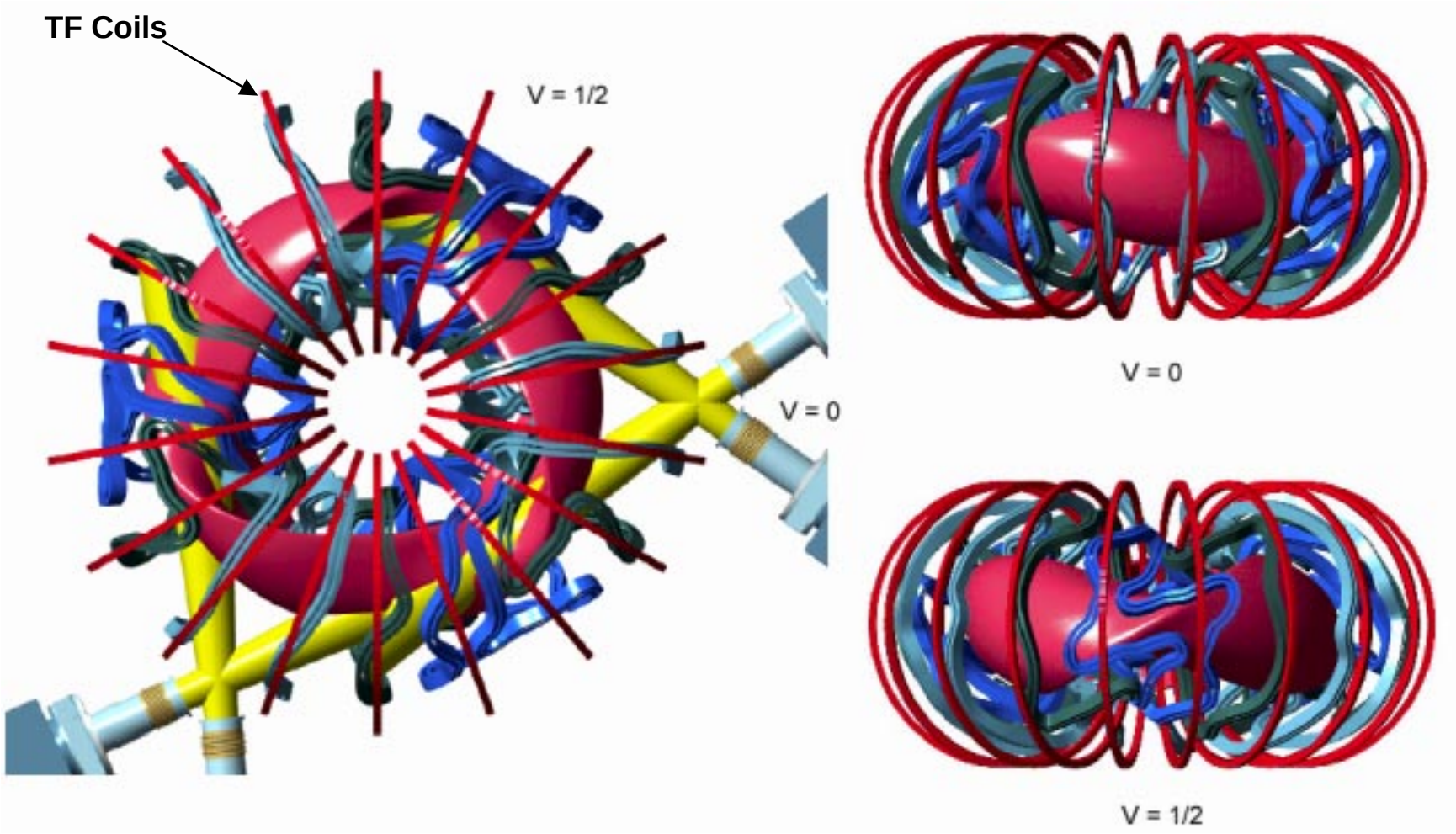
- **Limit conductor current to ~ 24 kA peak to match with existing TFTR power supplies**

Modular coil configuration

- 18 coils, 3 field periods, no coils on symmetry planes.
- Optimized for physics performance consistent with NBI access and engineering constraints.
- Coils wound with flexible cable conductor into cast-and-machined forms.
- Assuming ±1.5 mm tolerances; studies in progress to assess sensitivities to errors.
- Coils pre-cooled to LN_2 temperature to allow high current density.



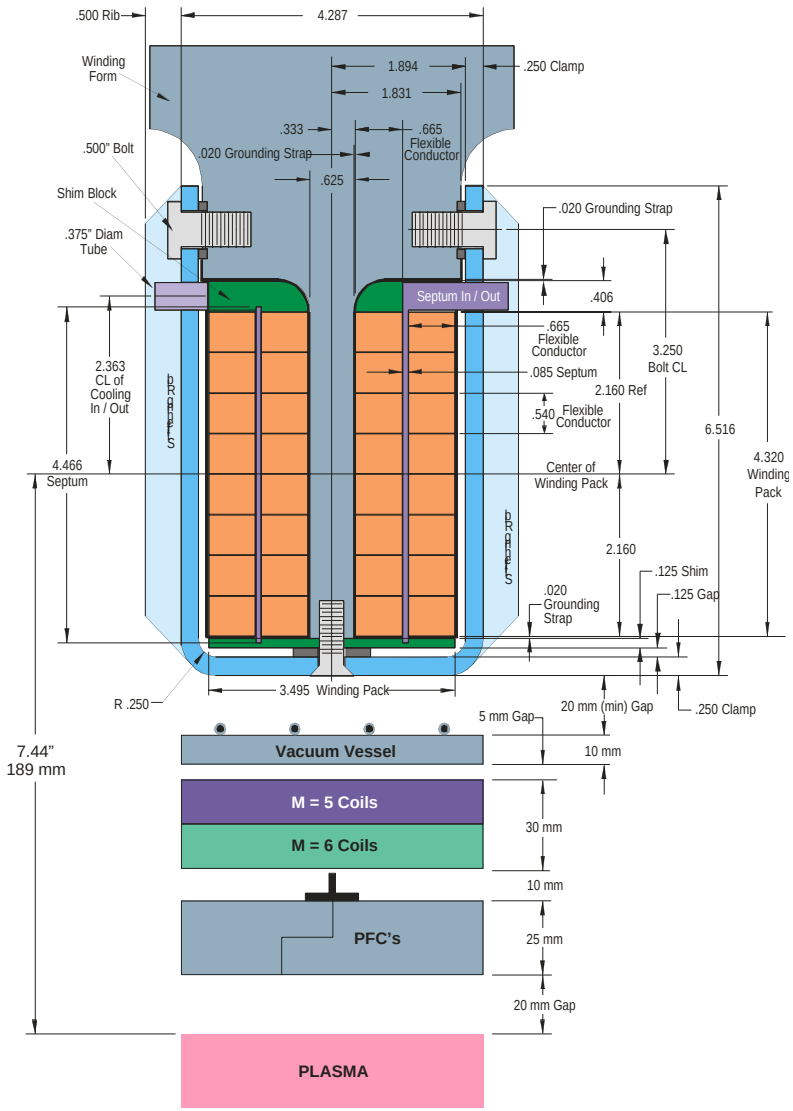
New Coil Design Provides Excellent Access



Continuous shell forms robust structure

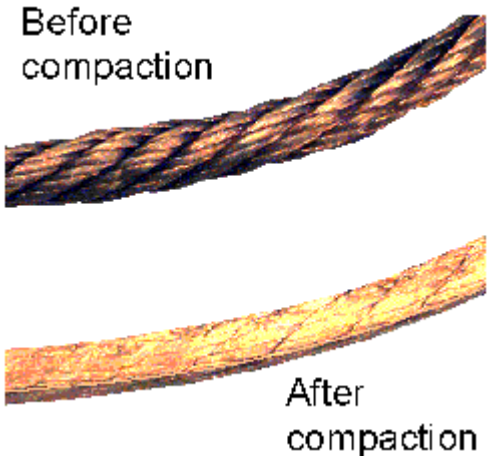
- **Shell consists of individual modular coil forms that are bolted together**
- **Penetrations for access are provided wherever needed**
- **Preliminary stress analysis indicates stresses are generally within allowables.**
  - Local problems can be solved with minor changes in thickness.

Modular coils are wound with flexible cable directly on coil structure



- **Parameters:**
- Coil Envelope = 2 x 110 x 37 mm
- Current / Coil = 649-kA @ 2-T
- Number of Turns = 32
- Nominal current / turn = 20.3 kA
- Conductor Size = 13 x 16 mm
- Net Current Density = 14-kA/cm2
- Total peak power ~ 55 MW

- **Flexible cable used to wind coil.**



Modular coil manufacturing sequence

- **Continuous support for strength and accuracy of windings**
- **Shell segments repeat 6 times for coils 1 thru 3**

Rough casting

Features are machined

Conductor wound directly into structure

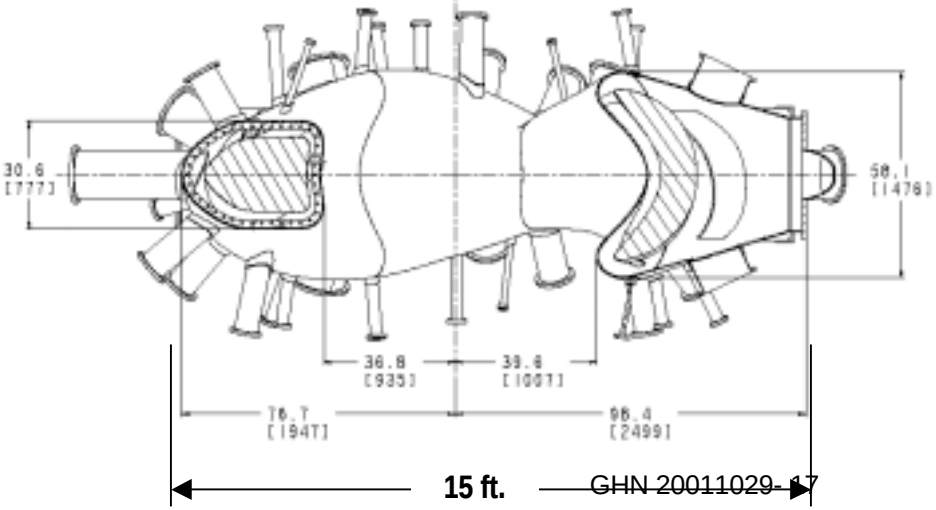
Auxiliary support clamps are installed

Vacuum vessel requirements

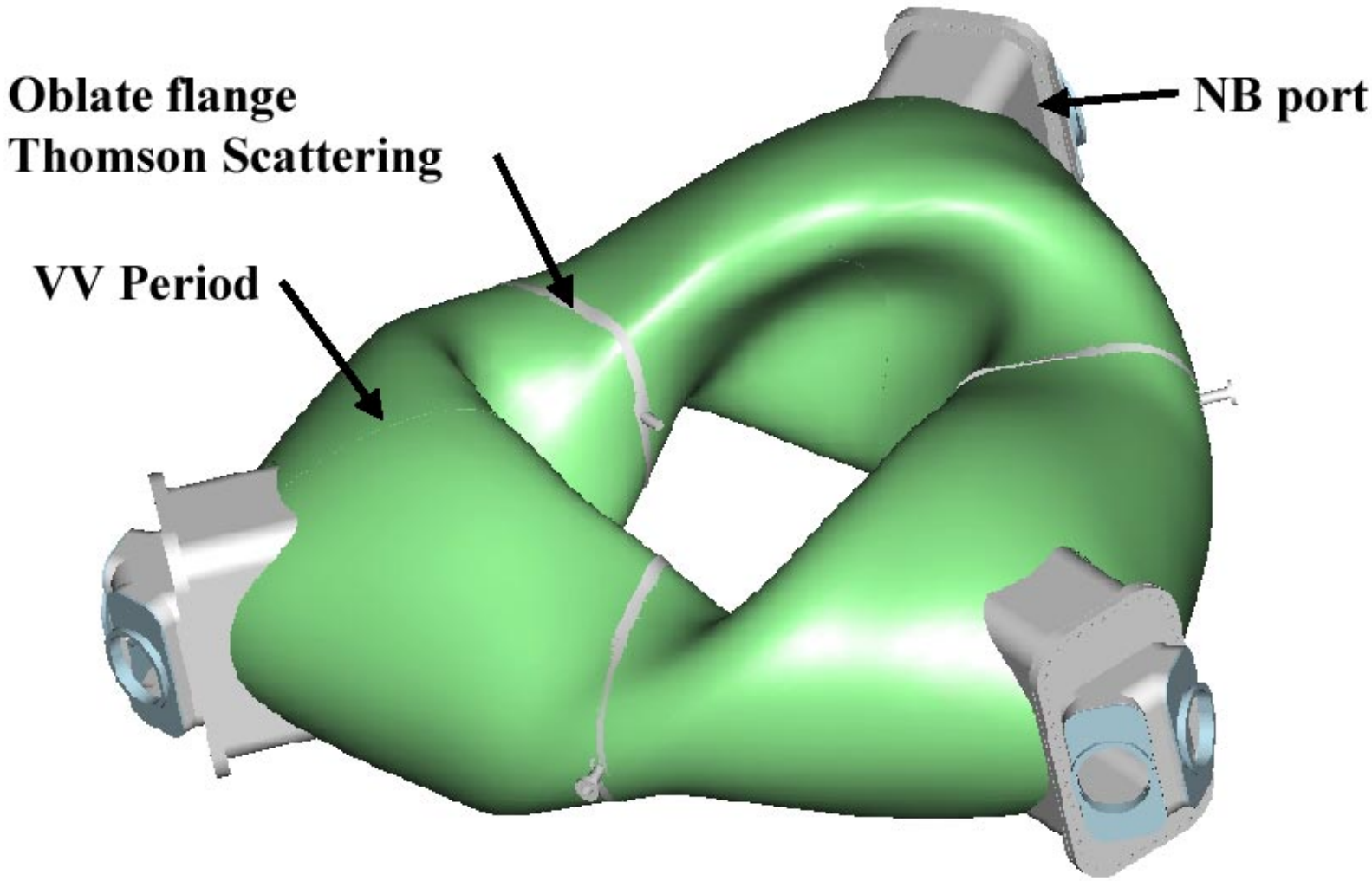
- **Vessel must be bakeable to 150 C**
- **Low permeability (< 1.02 nominal goal)**
- **Provide as large a volume as possible for plasma shape flexibility and power and particle handling systems**
- **Provide support for internal components such as internal liner, trim coils, magnetic sensors**
- **Provide access ports for diagnostics, vacuum pumping, heating systems, and personnel access**

Vacuum vessel design concept

- **Shell material** **Inconel 625**
- **Thickness** **.375 inch**
- **Time constant** **< 10 ms**
- **Total wt w/ports** **~ 12000 lbs**
- **Bolted joints connect field periods**
- **Traced with He gas lines for heating (to 150C) and cooling**
- **Combination Microtherm and Solomide foam insulation between VV and cold mass**



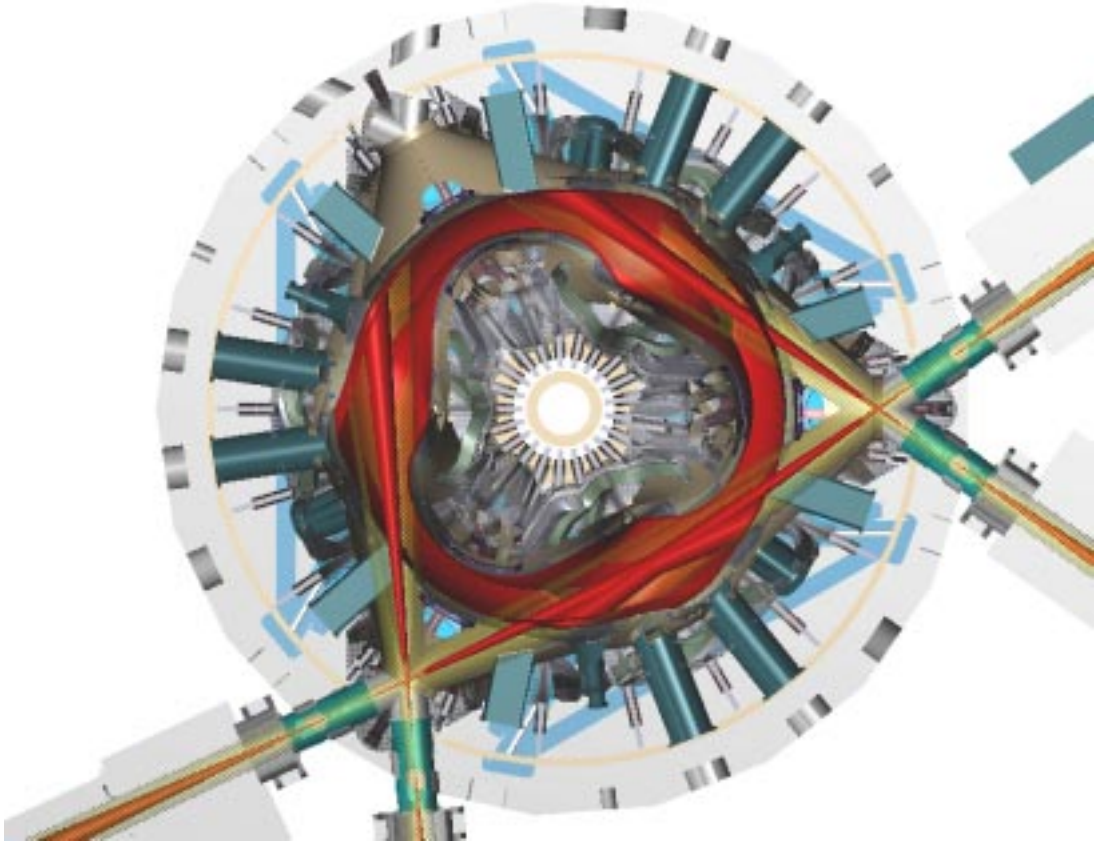
Vacuum Vessel Configuration



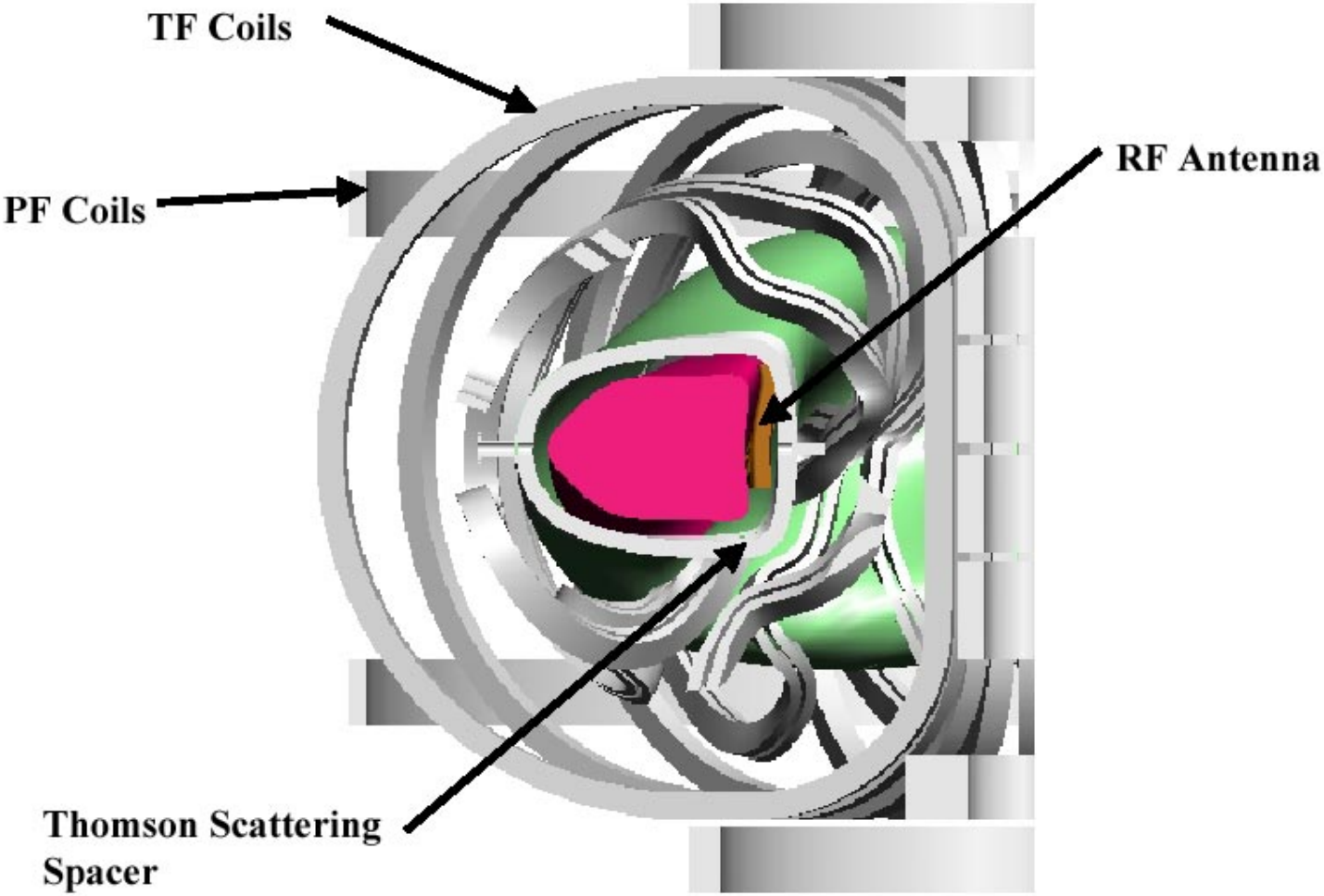
- **New shape provides more plasma-first wall clearance and space for PFCs.**

Access for tangential NBI

- Up to 4 neutral beams in combinations of co- and counter-
- Vacuum pumping through NB ducts

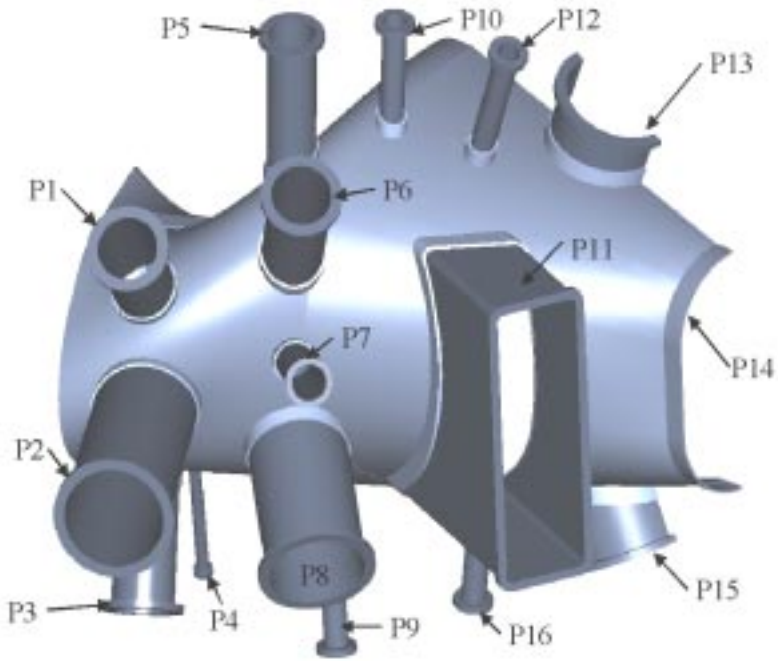


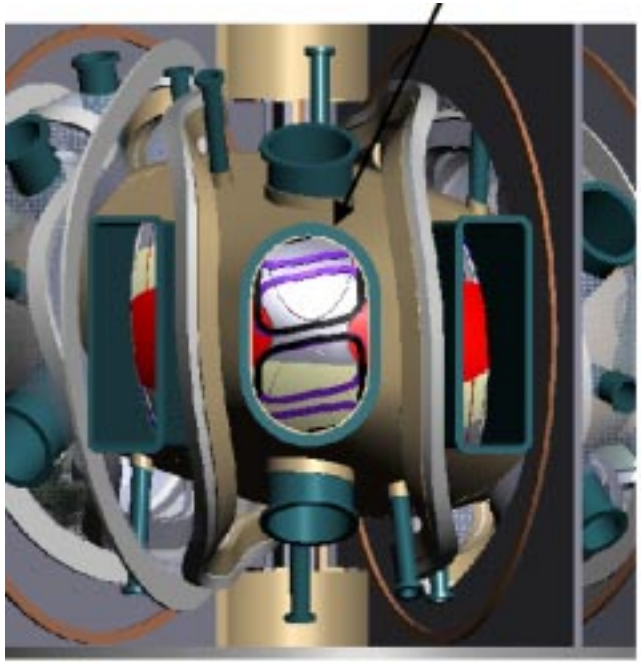
Access for Inboard RF Launcher



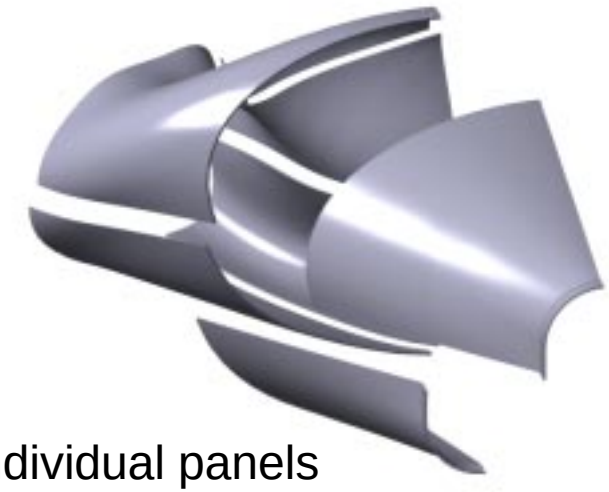
Diagnostic and personnel access

- 87 separate ports for ~100 different diagnostics
  - The number and sizes of ports matches specific diagnostic needs.
  - New design provides Thomson scattering access to oblate symmetry cross section.
  - Geometric requirements for specific diagnostics will be addressed in more detail during conceptual design
- Personnel access available through NBI or adjacent large ports

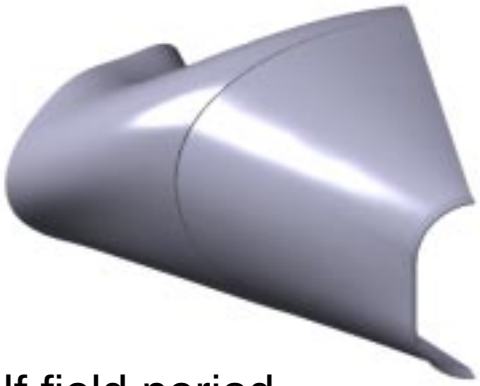




Vacuum vessel fabricated from formed panels



Individual panels



Half field period

Full field period with port stubs

PFC requirements

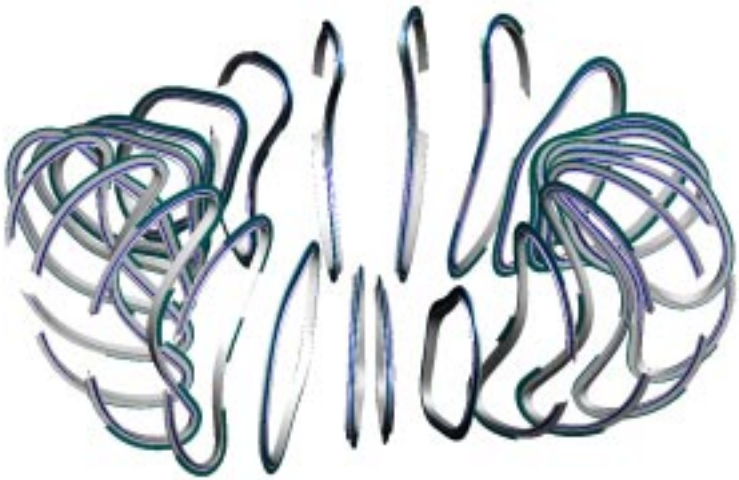
- **Basic requirements**
  - Carbon based, bakeable to 350C
  - Poloidal limiters, minimal coverage initially.
  - Provide penetrations, accommodate in-vessel diagnostics mounted on VV.

- **Upgrade requirements**
  - Full coverage of surfaces with carbon
  - Provision for divertor
  - 12 MW for 1.2 s

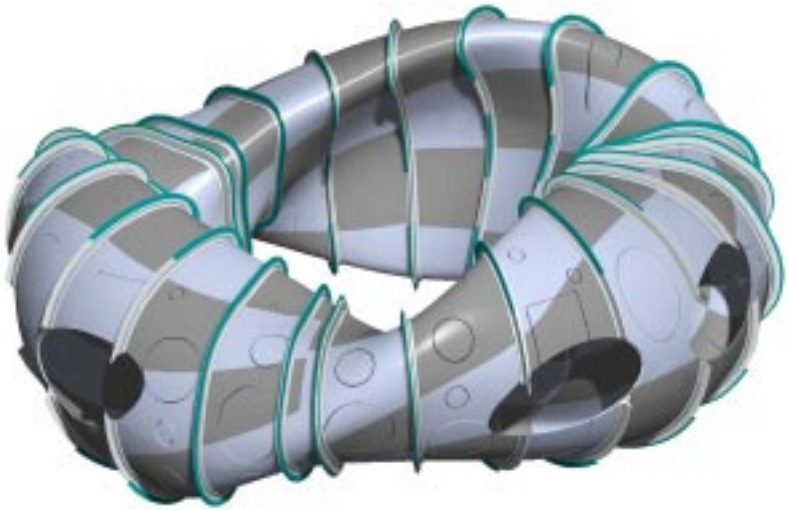
PFC design concept

- **Staged implementation planned**
  - Initial coverage with low Z poloidal limiters mounted on poloidal ribs.
- **Full coverage provided by mounting molded carbon fiber composite (CFC) panels on poloidal ribs**
  - Panel size based on advice from BFG aerospace (~ 60 cm square, 1 cm thick)
- **Ribs are separately cooled / heated with He gas for bakeout (350C) and normal operation**
- **Ribs are registered toroidally to VV but allowed to grow radially and vertically**

Poloidal ribs

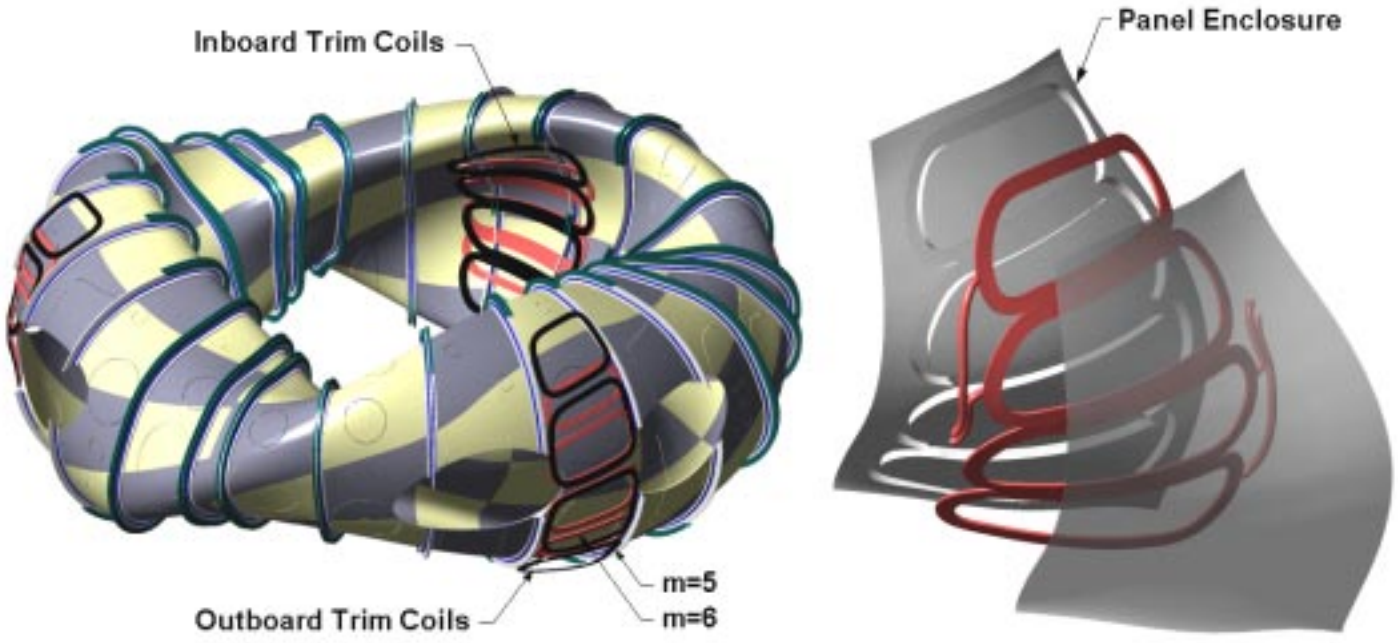


CFC panels mounted on poloidal ribs



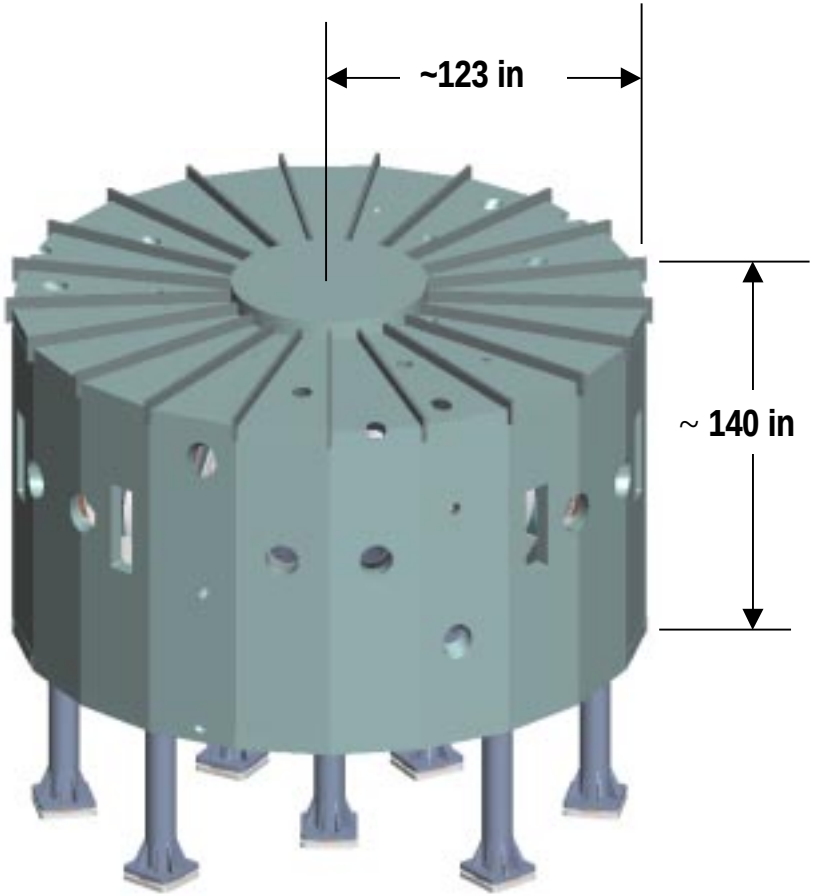
Trim coils

- Provided to mitigate field errors on m=5 and m=6 resonant surfaces
- Located close to inboard and outboard midplane at v=0 cross-section
- Mounted off vacuum vessel, behind liner
- Canned for vacuum compatibility



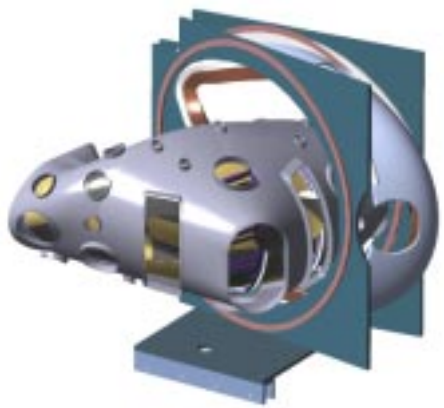
Cryogenic coils enclosed in a common cryostat

- Cryostat design uses commercial concept - substructure sprayed with urethane foam
- Inexpensive construction facilitates maintenance access
- Holes provided for all vacuum vessel port extensions
- Silicon rubber “Gortiflex” boots to seal between vessel port extensions and cryostat
- 8” thickness reduces heat leaks to 2kW but still will require local heaters/blowers to avoid condensation

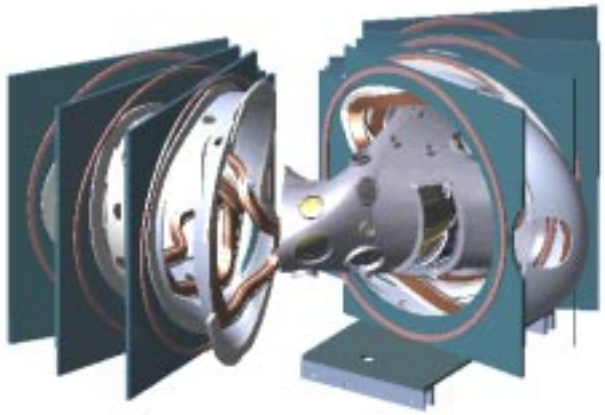


Modular and TF coils and VV will be pre-assembled in field periods

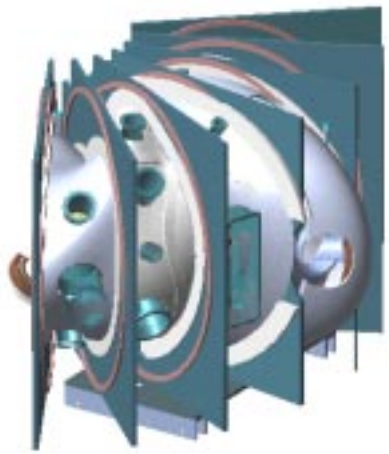
- **Adequate space exists in NCSX test cell for pre-assembly of field periods**
- **TFTR test cell might be an even better place for pre-assembly (more space for pre-assembly, more space in NCSX test cell for final assembly)**



Vacuum vessel is sized so that coils can slide over completed period.

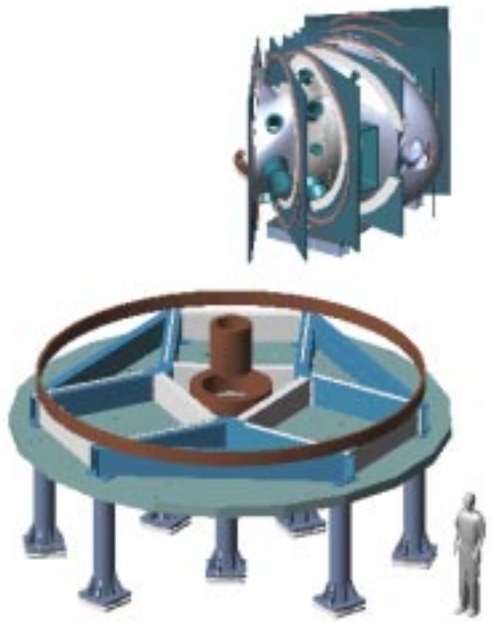


3-coil assemblies installed on each end to create 6 coil period.

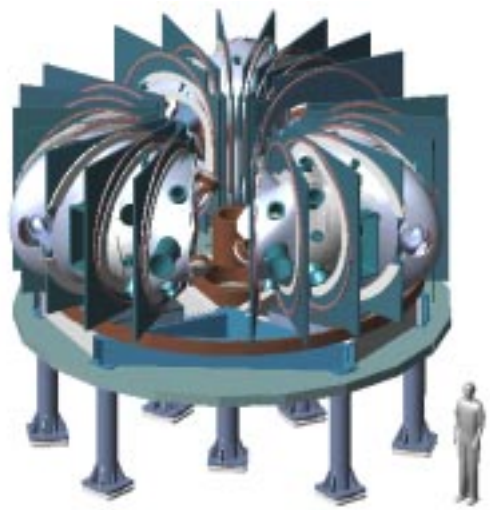


Port extensions added to vessel to complete field period subassembly

Field periods are assembled on machine structure in NCSX test cell



Field period lowered onto machine base in position 18 inches radially outward

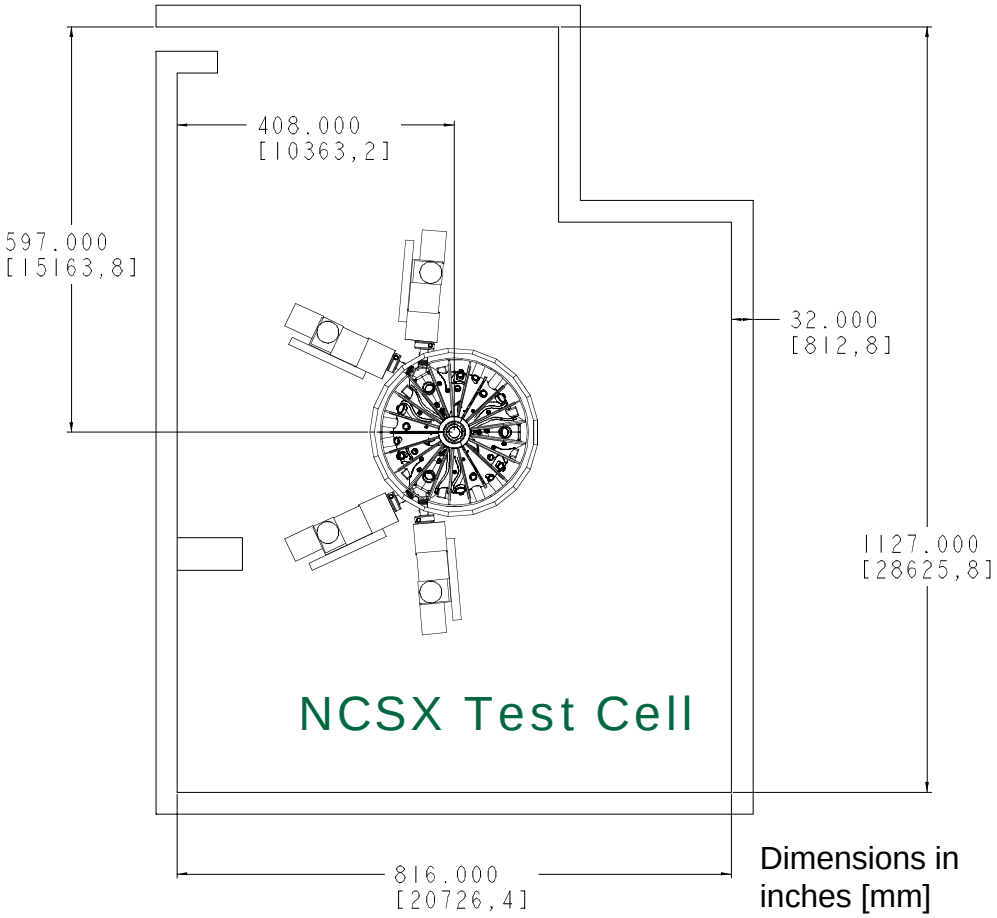


3 field periods prior to radial assembly step

Field periods connected after radial motion, PF coils raised/lowered into position

There is ample room for NCSX in the combined PLT and PBX test cells

- **The combined test cell can easily accommodate four beamlines.**
- **Field periods can be pre-assembled in either the NCSX or TFTR test cell**



Dimensions in inches [mm]

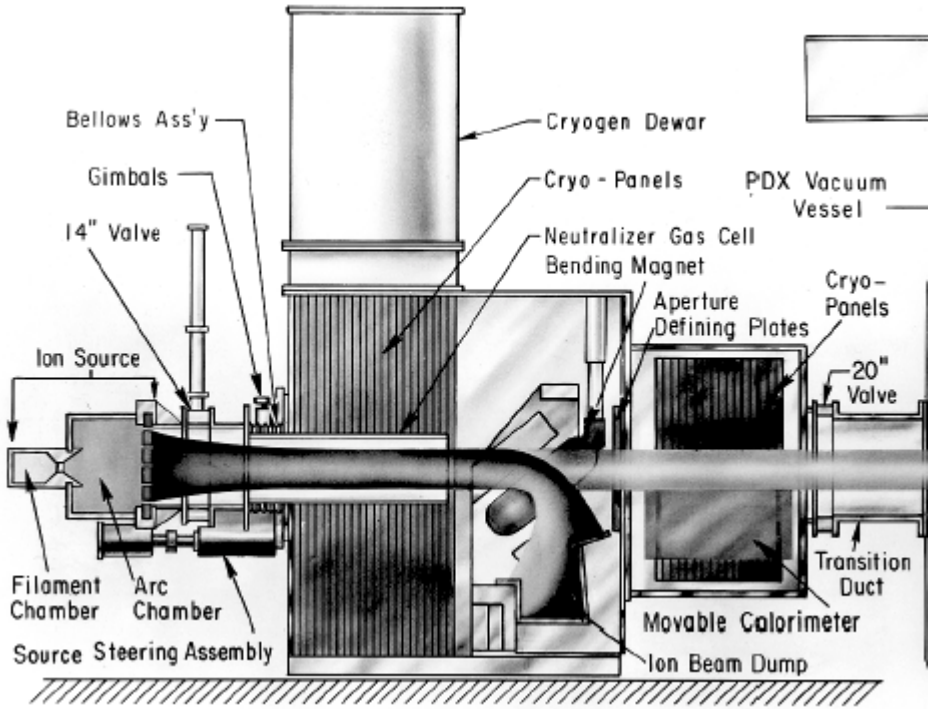
The PBX and PLT control rooms will be refurbished into a single large control room

- Space is available in adjacent rooms for offices and computers

A portion of the former PBX-M Control Room

NCSX will re-use the 6MW PBX-M neutral beam system

- The four beamlines will be stored and refurbished at D-site
- Two of the four beamlines will be installed initially and supply 3MW of heating power - the other two beamlines can be added later on
- NCSX must accommodate 6MW of ICRF heating in addition to the 6MW of NBI
- 7-8MW of RF power (20-30MHz, suitable for mode conversion RF heating) is available from the 4 FMIT sources located in an area adjacent to the NCSX Test Cell



TFTR power supplies will be re-used for the modular, TF, and PF Coils

- **TFTR power supplies will be shared with NSTX**
- **Switching can be accomplished in a matter of minutes**
- **PBX Robicon power supplies will be used for the trim coils**

TFTR Power Supply Building

TFTR Power Supplies

Existing cooling systems will be re-used

- **The de-ionized water cooling system will serve the neutral beams, diagnostics, vacuum pumps, and vessel cooling**
- **The PBX-M neutral beam helium refrigerator will supply helium for the neutral beams**
- **A new 15,000 gallon LN2 tank will be located next to the existing tank for cooling the cryogenic (modular, TF, and PF) coils and structure**

Project Status and Plans

Recent reviews were very positive

- DOE Physics Validation Review (March, 2001):
  - Endorsed QAS concept, overall NCSX physics design approach.
  - DOE approved “Mission Need”, start of conceptual design.
- Fusion Energy Sciences Advisory Committee [FESAC] (May, 2001):
  - Designated NC SX as a proof-of-principle experiment.
  - FESAC: Its “gains earn for the compact stellarator an important place in the portfolio of confinement concepts being pursued by the US Fusion Energy Sciences program.”

Project is now in conceptual design

Plans for conceptual design

- **Develop engineering solutions to meet requirements**
  - Finalize requirements.
  - Establish defensible and achievable dimensional tolerances.
  - Conduct necessary analysis.
  - Focus on novel or unusual aspects (modular coils, vacuum vessel).

- **Optimize for manufacturability, involving industry**
  - Several manufacturing study contracts to be awarded in November.
  - Will obtain feedback on how to improve design, reduce costs, sensitivity to tolerances, R&D needs.

- **Develop cost and schedule estimates that meet established targets.**
  - Need to determine critical path activities.
  - Pursue cost effective design and manufacturing solutions

Conceptual Design Review planned for April, 2002.

Summary

- **A robust design concept that meets performance requirements has been developed.**
- **Site provides ample space and valuable site credits**
- **Configuration has been improved to provide better access, more in-vessel space for PFCs and launchers, consistent with required physics properties.**
- **Requirements are nearly finalized.**
- **Project is on track for April, 2002 CDR.**