The ORNL Compact Stellarator Program

J. F. Lyon

ORNL Stellarator Program Coordinator

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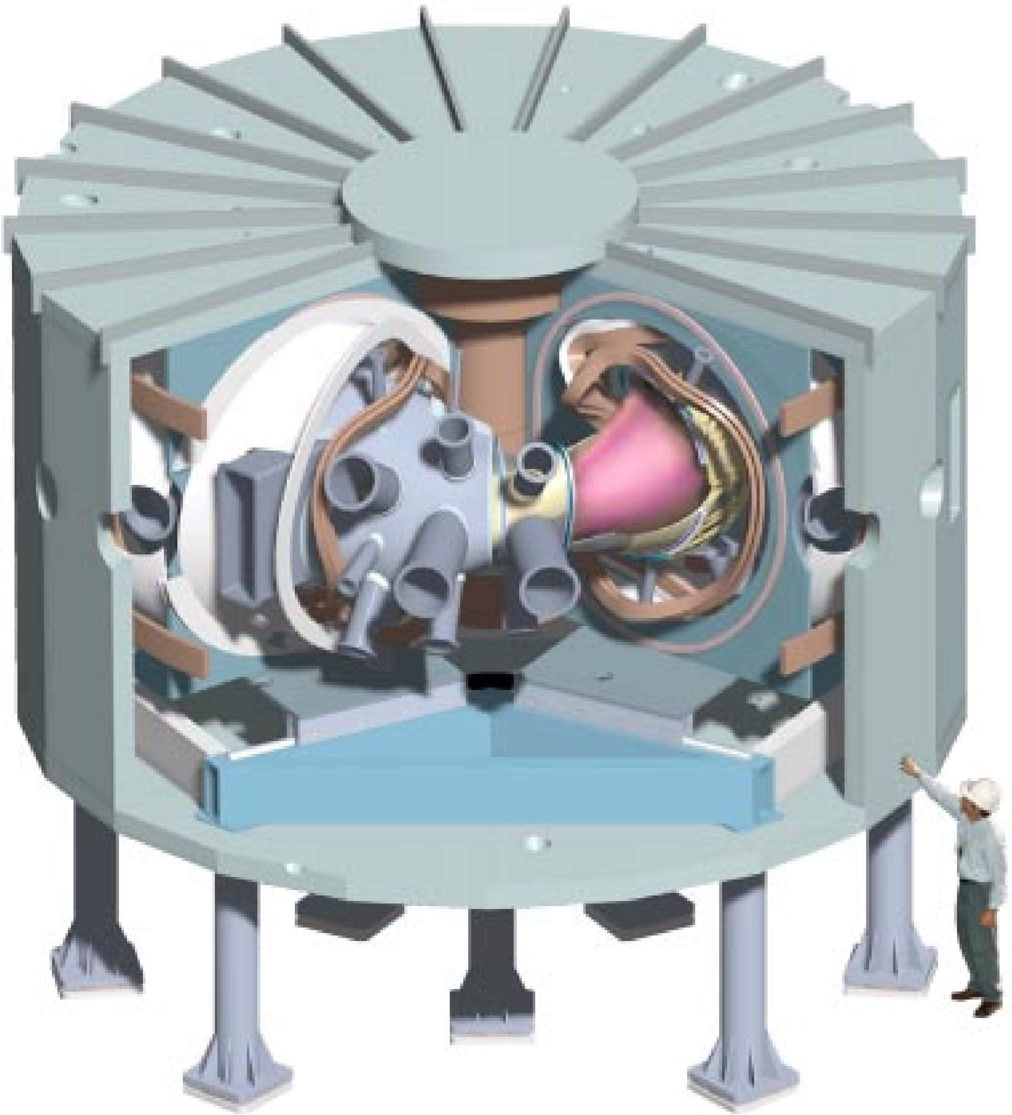
Over the past 6 years ORNL has worked on development of a new type of magnetic confinement concept for fusion research.

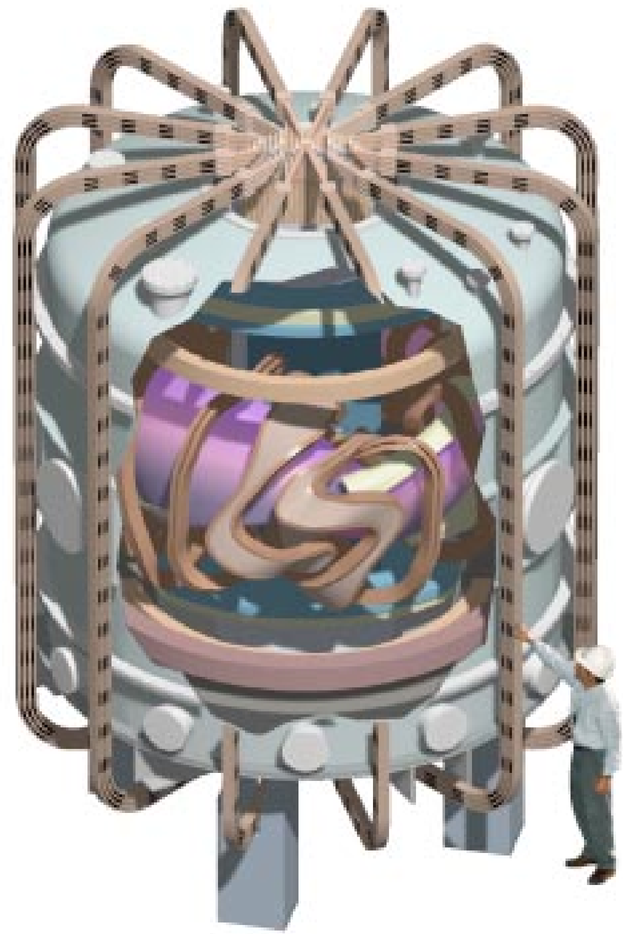
The ORNL effort has resulted in two new plasma experiments: the 70M$ National Compact Stellarator Experiment at Princeton and the 15 M$ Quasi-Poloidal Stellarator at ORNL.

ORNL Is Designing Both Compact Stellarators

NCSX



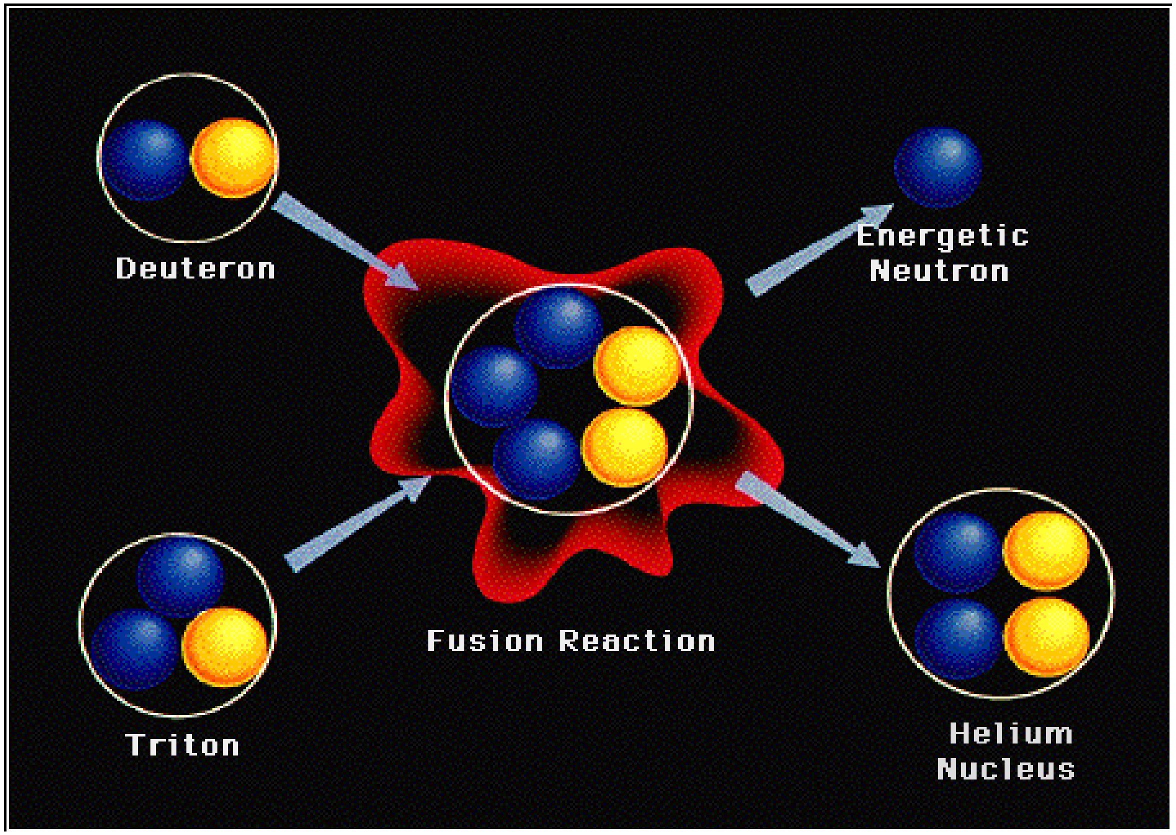
Q PS



TOPICS

- Fusion, Plasmas and Magnetic Confinement
- Reasons for Fusion Research, Progress
- Approaches: Tokamaks and Stellarators
- Quasi-Symmetry
- National Compact Stellarator Experiment
- Quasi-Poloidal Stellarator
- Vacuum Issues

Fusion Is the Combining of *Light Nuclei* to Form a *Heavy Nucleus* and *Energy*

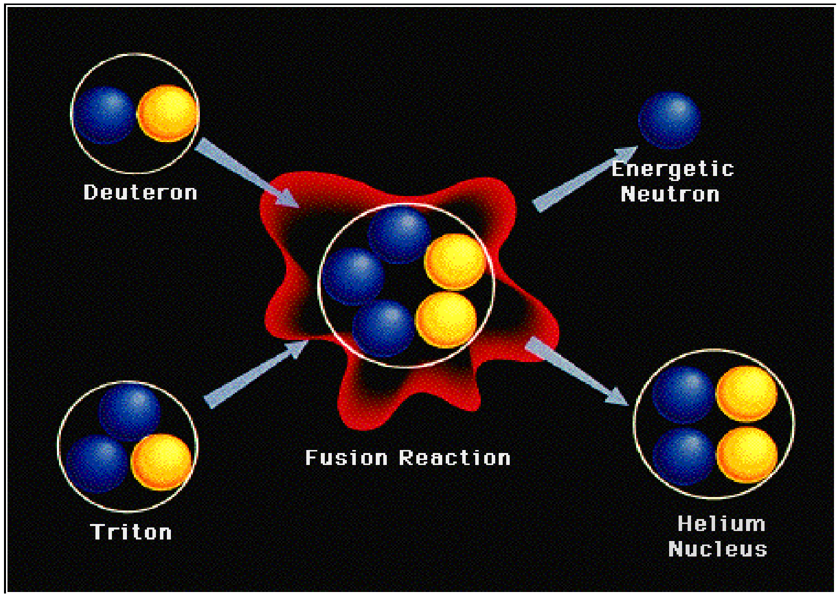


$E = mc^2 \Rightarrow$ energy ~ million x chemical energy

Examples: the sun & stars, the H-bomb

Necessary Conditions for Fusion

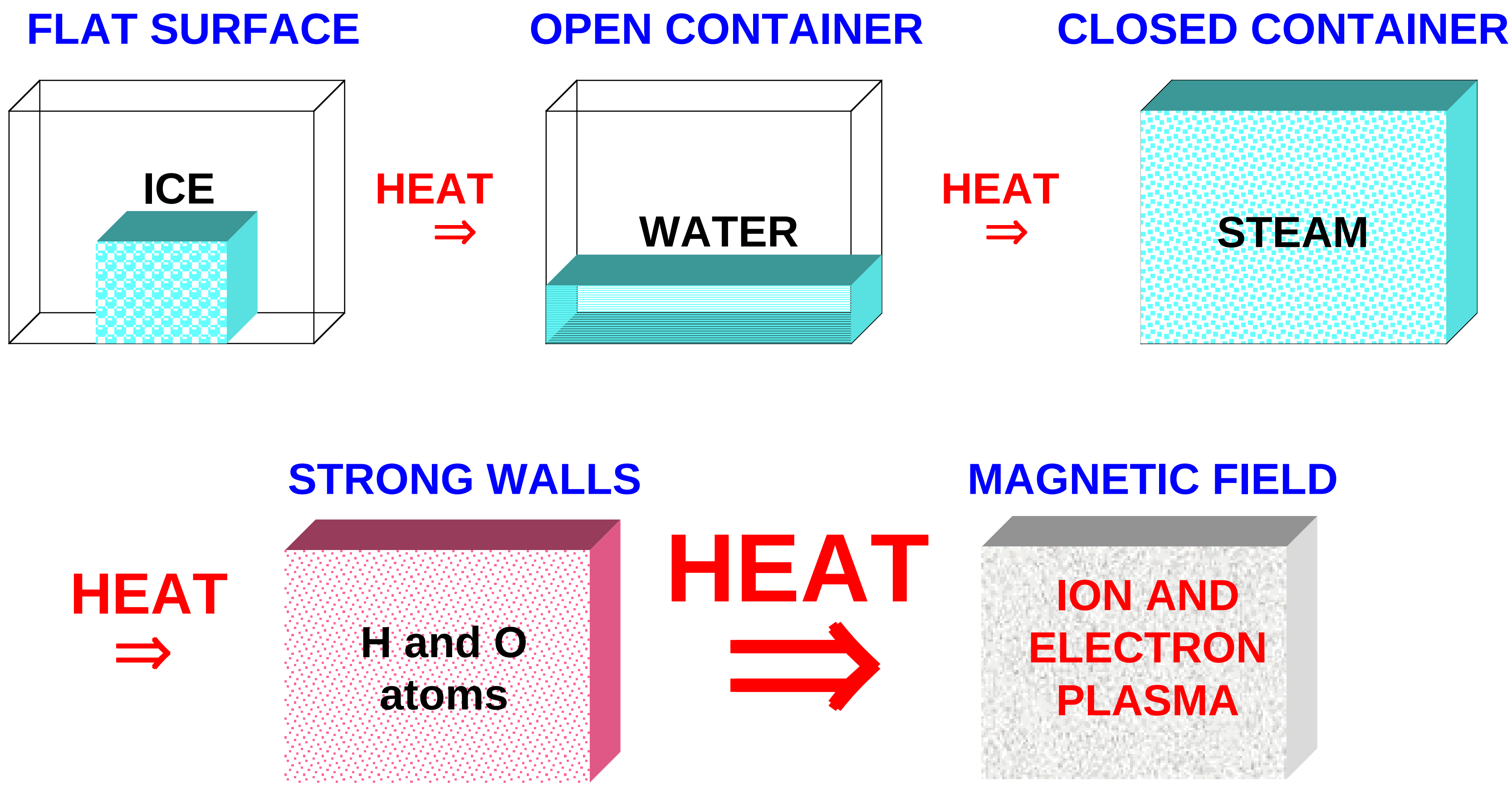
- **The *energy of* the nuclei must be high enough to overcome their repulsive force**
  - ⇒ **Temperature ~ 200 million degrees**
  - ⇒ **Must be a *plasma***
- **Confinement: Hold plasma at high enough density and contain the heat long enough to produce more power than is required to heat the plasma**



- **Generating net electrical power requires**
  - ⇒ **Density ~ 1/200,000 of atmospheric density**
  - ⇒ **Pressure ~ 5 atmospheres**
  - ⇒ **Confinement time ~ 1 - 2 seconds**
  - ⇒ **No contact with material walls!**

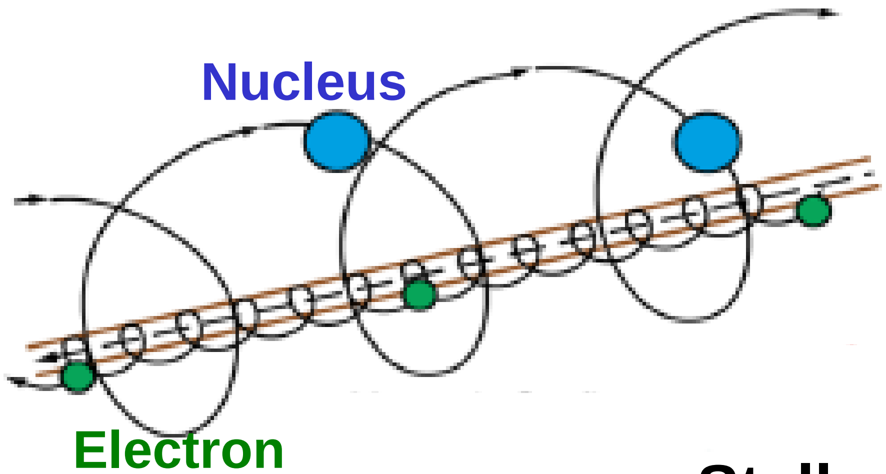
Plasma is the Fourth State of Matter

CONTAINMENT REQUIRES

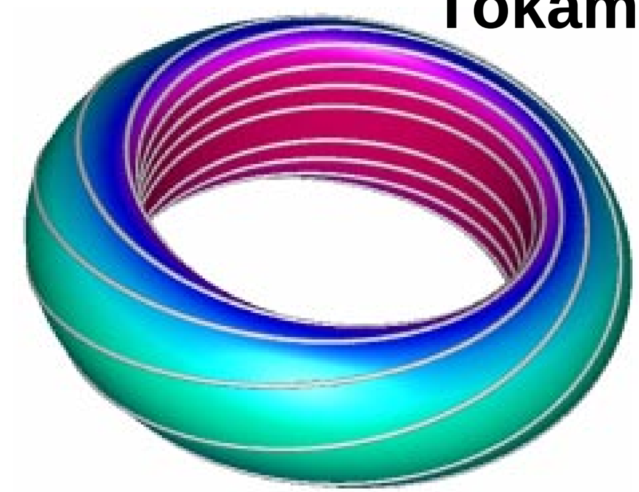


Magnetic Fields Are Used to Confine the Hot Plasma

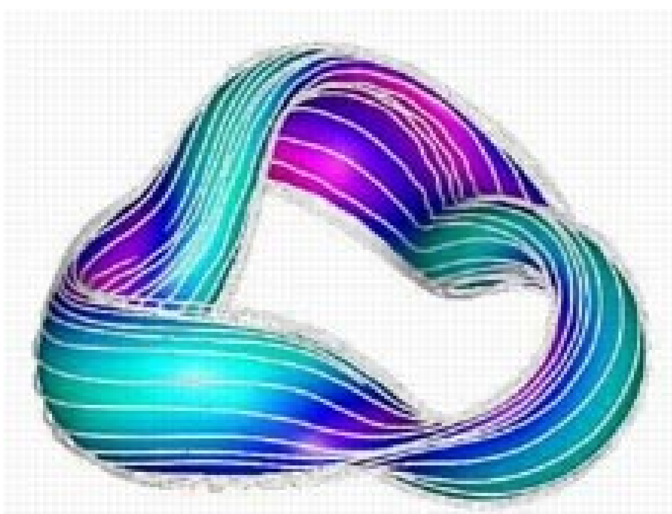
Magnetic Confinement

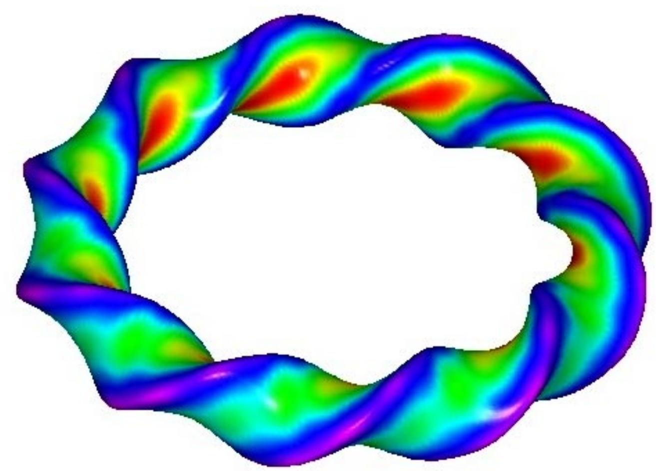


Tokamak



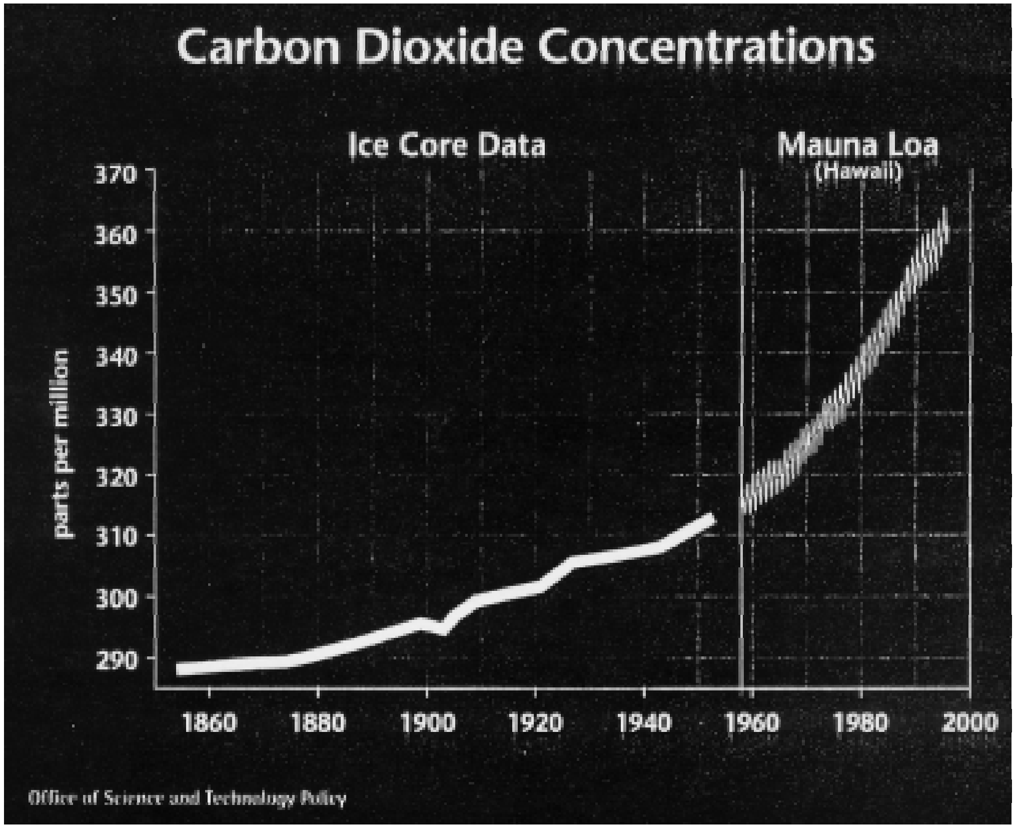
Stellarators



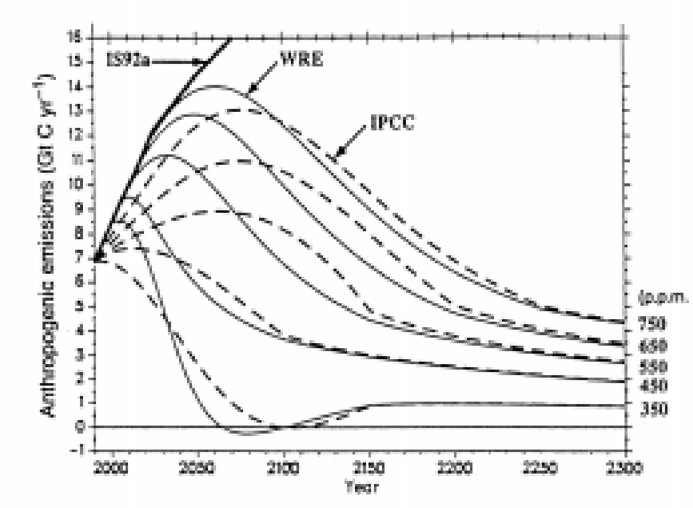


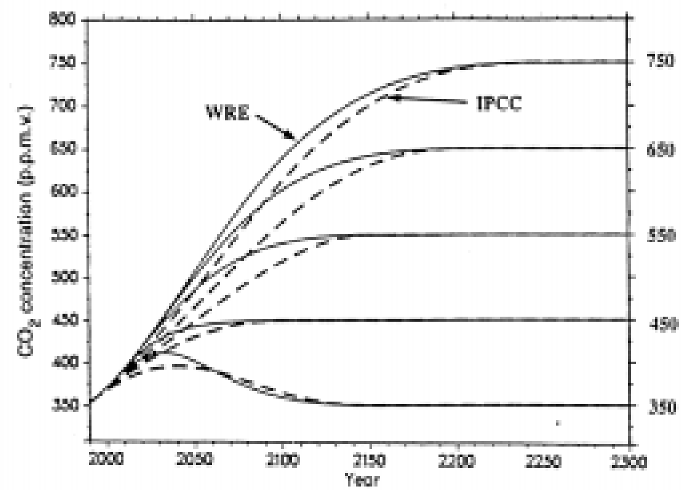
Critical Need for Non-Fossil-Fuel Energy Sources

- **Atmospheric concentration of CO_2 has been increasing exponentially**
- **Projected climate changes for which scientific confidence is high**
  - **5-25 foot rise in sea level**
  - **20-50% drying out of U.S. summer soil moisture**
  - **Near shutoff of N. Atlantic ocean overturning**
- **Major increase in summer heat index (July, Southeast U.S.)**
  - **Present ~ 87 ºF**
  - **2 x $CO_2 \Rightarrow$ 98 ºF**
  - **4 x $CO_2 \Rightarrow$ 110 ºF**

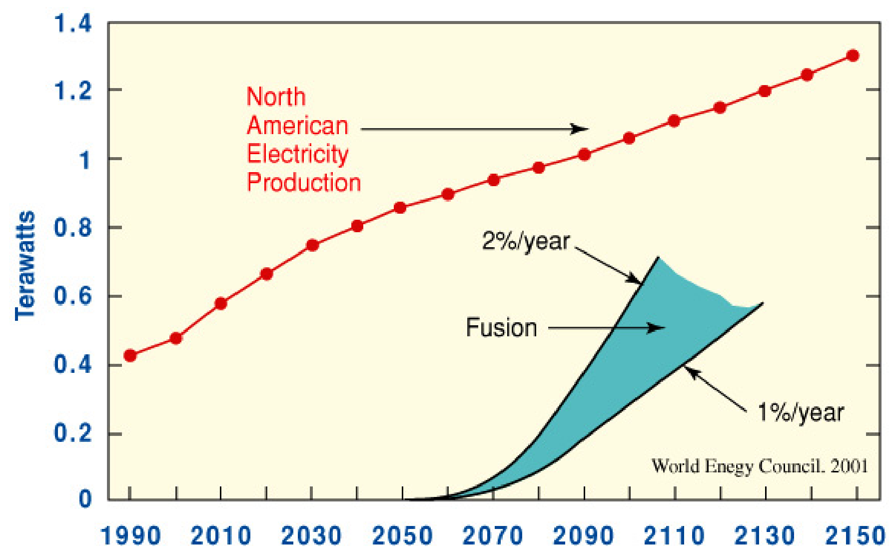


Fusion can Contribute to Long-term Stabilization of Atmospheric Greenhouse Gases



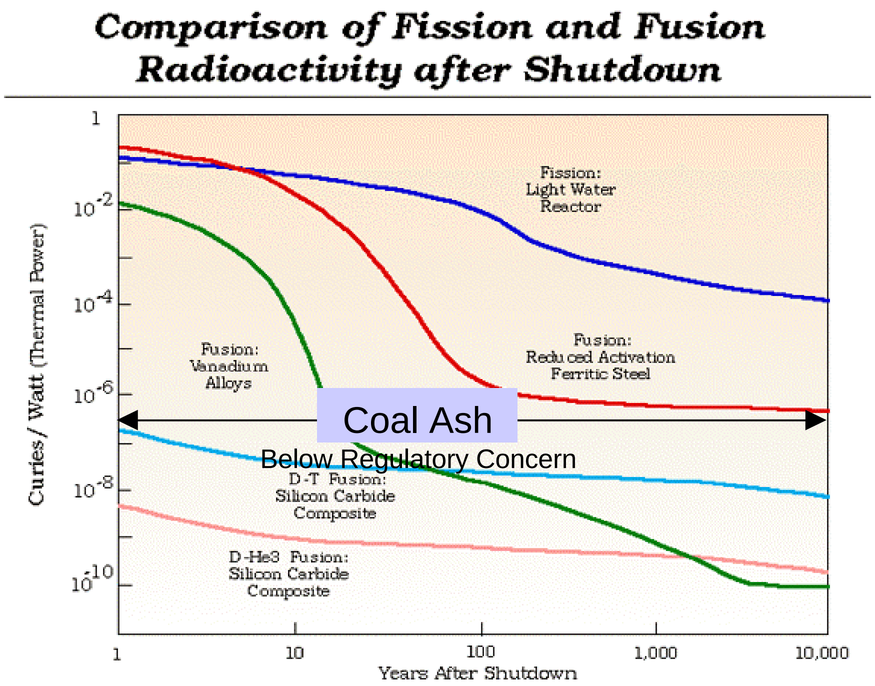


To stabilize at reasonable levels, non-carbon emitting sources must provide about half of the world's power by about 2100.



Fusion Is Part of a Balanced Energy Strategy

- **Abundant fuel, available to all nations**
  - **Deuterium and lithium easily available for thousands of years**
- **Environmental advantages**
  - **No carbon emissions, low radioactivity - no Yucca Mountain**
- **Can't blow up, can't melt down**
  - **Less than 5 minutes of fuel in the plasma**
- **Low risk of nuclear materials proliferation**
  - **No uranium, thorium or plutonium**
- **Concentrated relative to solar, wind, biomass**
  - **Reduced land usage**



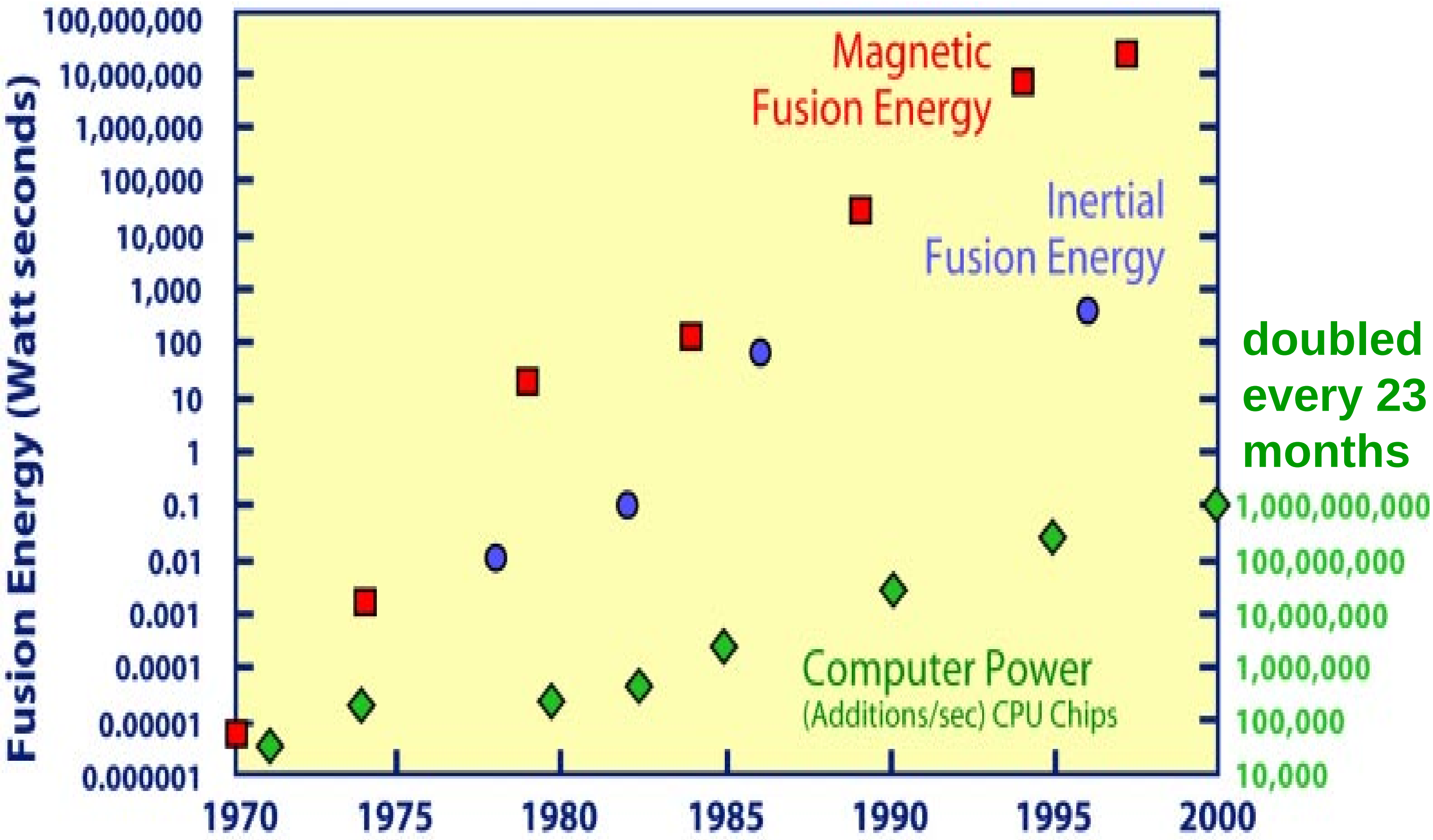
However, long-term government research support is required to demonstrate its practicality.

Requirements for a Fusion Reactor

- Need to keep high-temperature plasma away from walls
  - would cool and contaminate the plasma, destroy walls
    - $\Rightarrow$ need strong magnetic field
- Need better confinement than in usual approaches
    - $\Rightarrow$ use specially shaped (symmetric) magnetic fields
- Control of neutrals and impurity influx is needed for good plasma performance
- Need to divert escaping plasma into special chambers
- Needs to be economically competitive with other energy sources
    - $\Rightarrow$ Compact size for reduced capital cost
    - $\Rightarrow$ No/low power input to sustain the fusion plasma
    - $\Rightarrow$ Maximum plasma pressure for allowable magnetic field
      - Power produced proportional to pressure squared

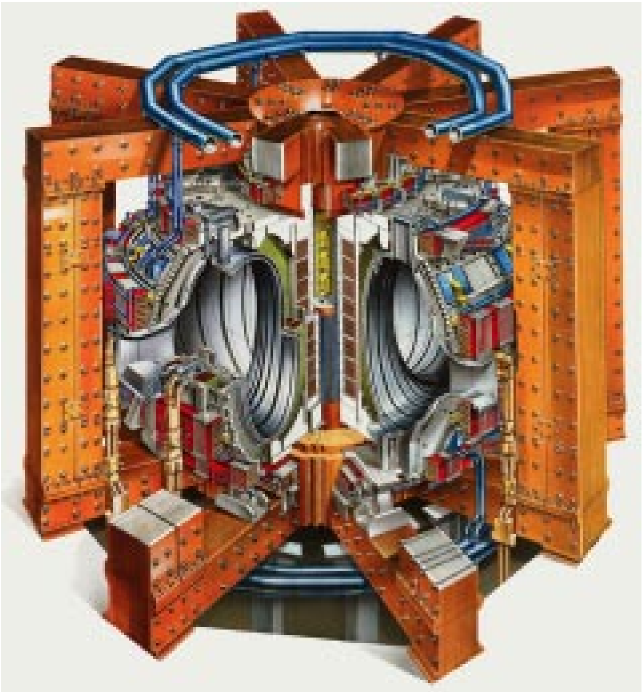
Fusion Power Has Increased at High Rate

Fusion Energy Produced (doubled every 8 months)

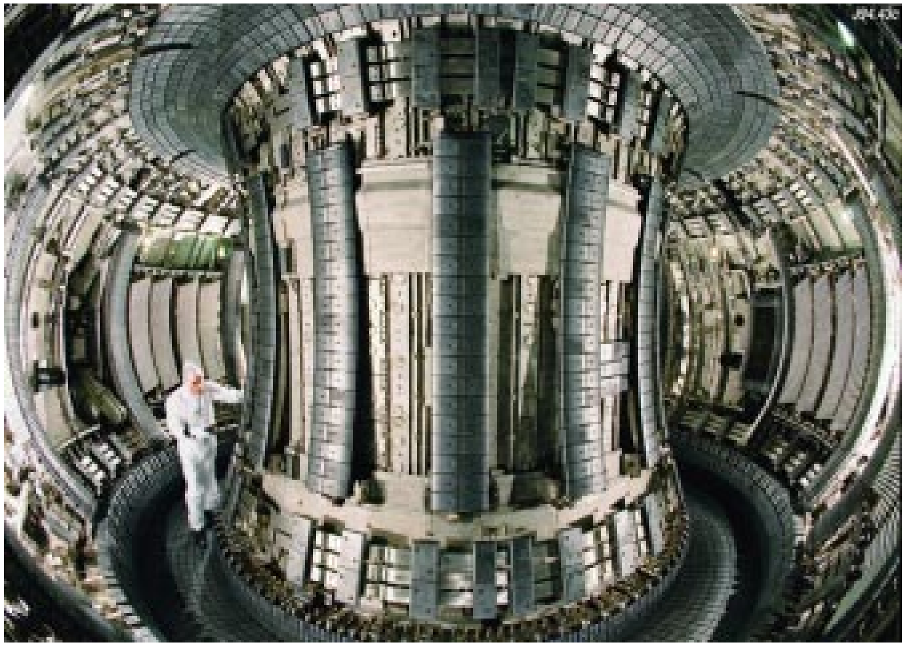


doubled every 23 months

Tokamaks are the Main Fusion Approach



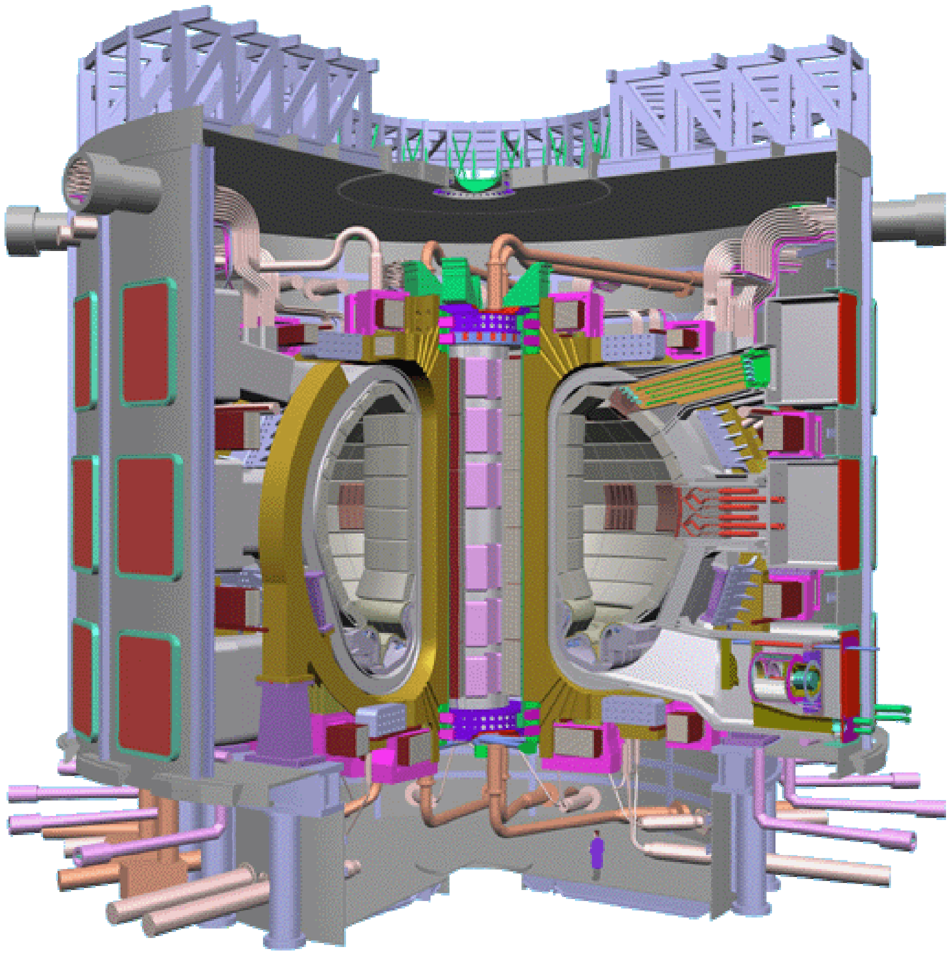
JET (Europe)



40 feet high, 60 feet in diameter

- **<u>Advantages</u> -- most developed, best performance (13 MW), compact ⇒ moderate size reactor**
- **<u>Disadvantages</u> -- large current in plasma, prone to disruptions, needs continual power and control of the plasma ⇒ not inherently steady state**

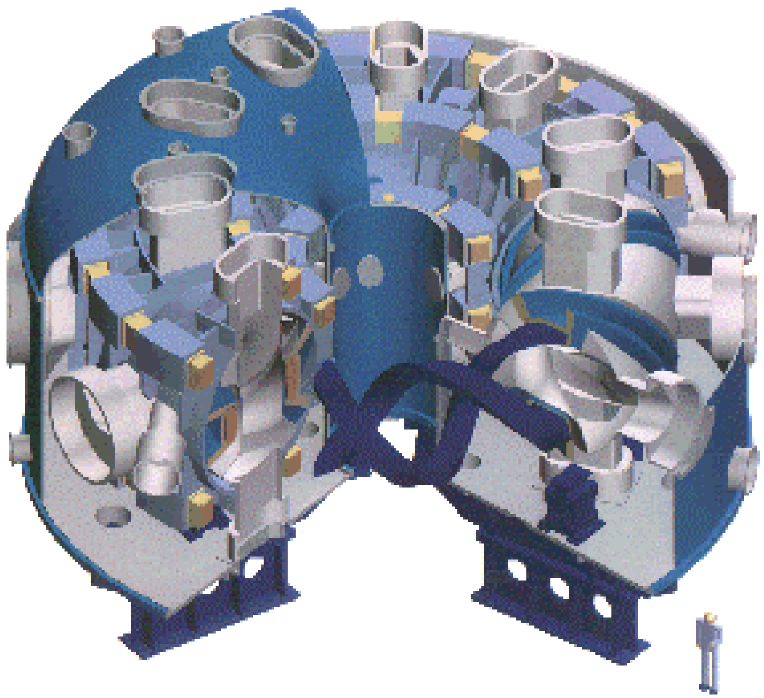
Next Step: Higher Fusion Power Production



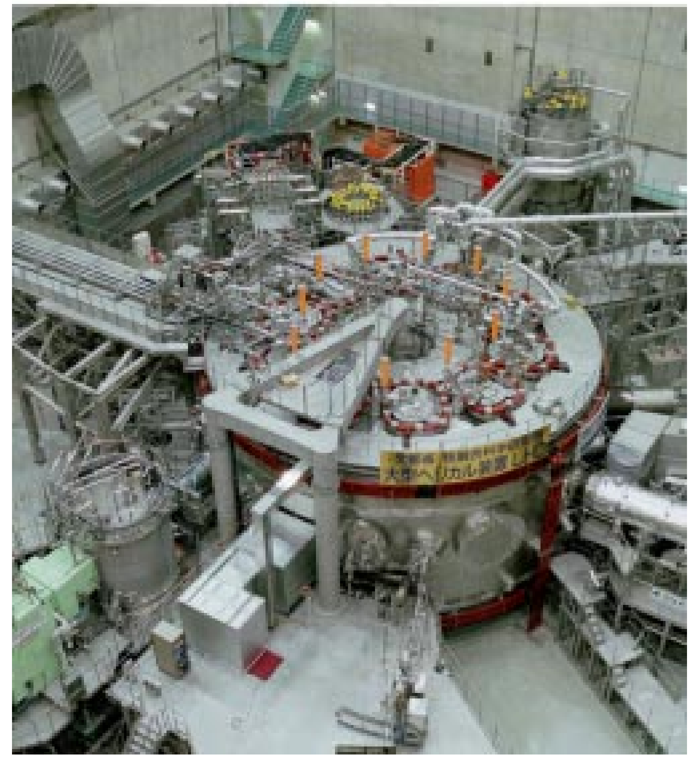
ITER Tokamak
(500 MW, $4.2 B)

95 feet high
95 feet diameter

Stellarators are the Second Approach

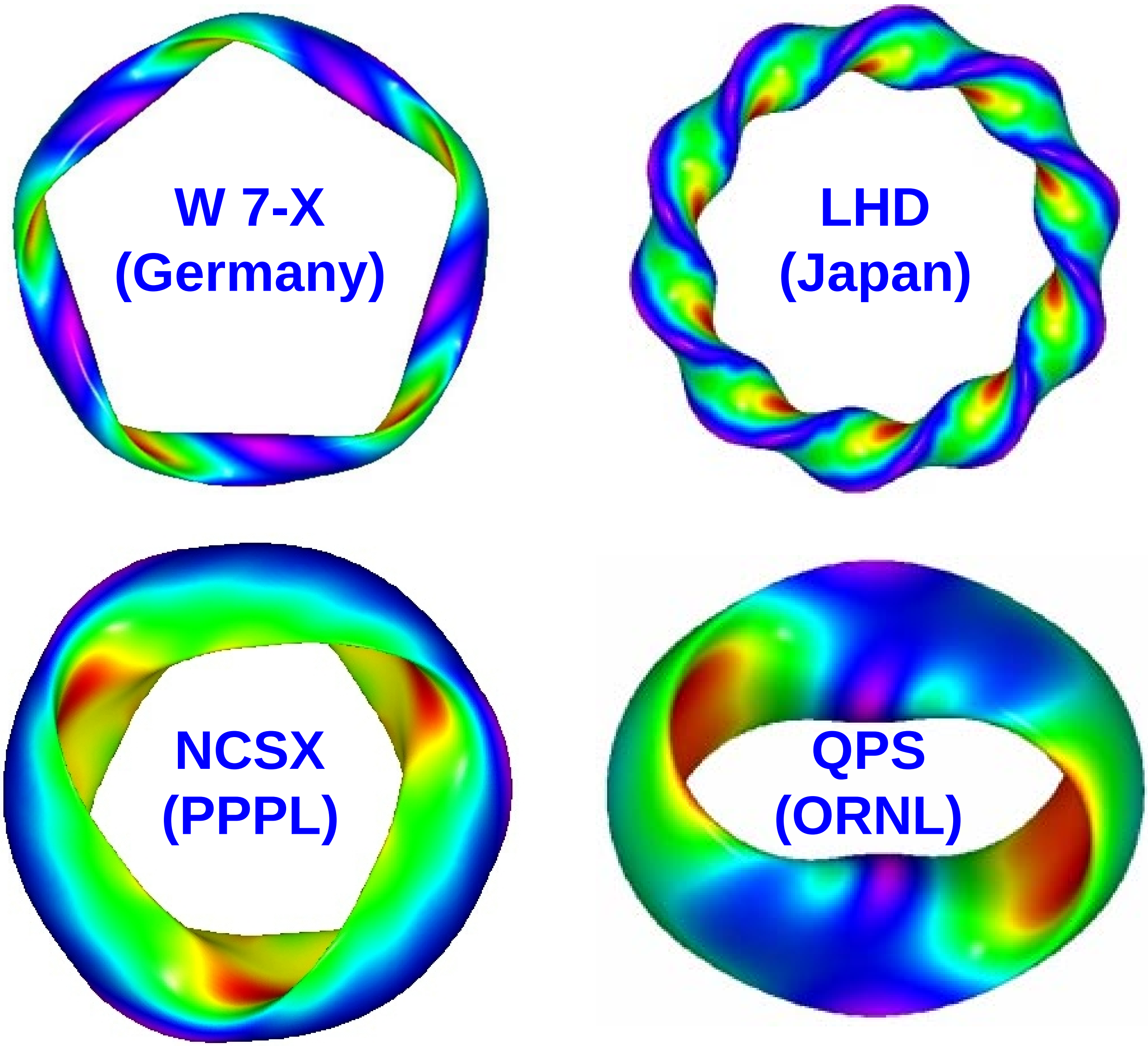


LHD (Japan)



- **<u>Advantages</u> -- no current in plasma, no power input needed for a reactor ⇒ inherently steady state**
- **<u>Disadvantages</u> -- skinny donut shape, more complicated plasma shape ⇒ very large reactor size**

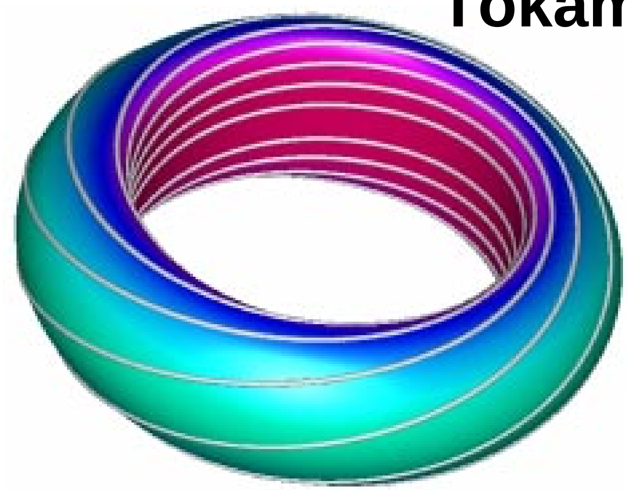
Compact Stellarators Allow Larger Plasmas



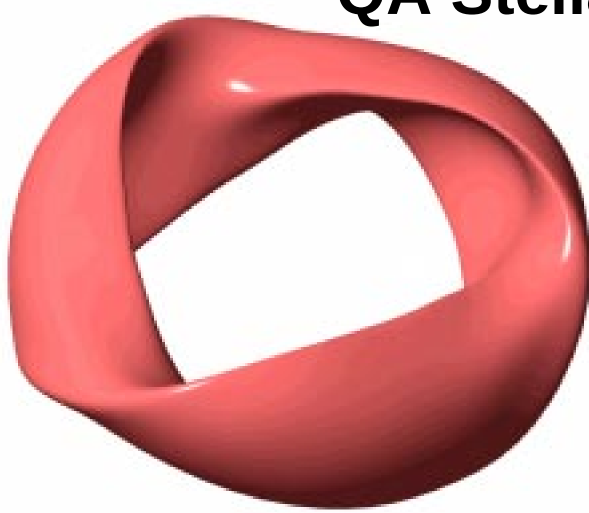
Magnetic Field Symmetry Is Important in Confining the Hot Plasma

- Symmetry is a very powerful tool in physics
  - example: physics same for uniform velocity ⇒ relativity
  - example: physics same for gravity or acceleration ⇒ general relativity
- Rotational symmetry
  - if plasma looks the same after rotation ⇒ properties don't vary in that direction, most particles are confined
- Symmetry in magnetic field system
  - tokamak and QA stellarator have the same properties
- Other types of symmetry exist
  - poloidal, helical ⇒ US program

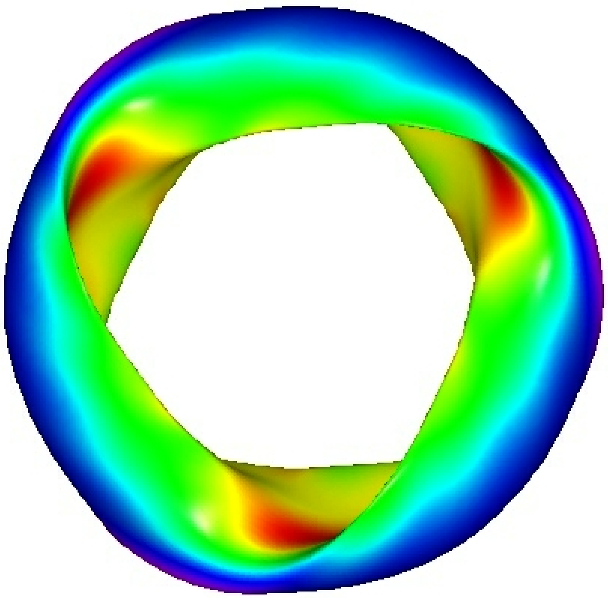
Tokamak

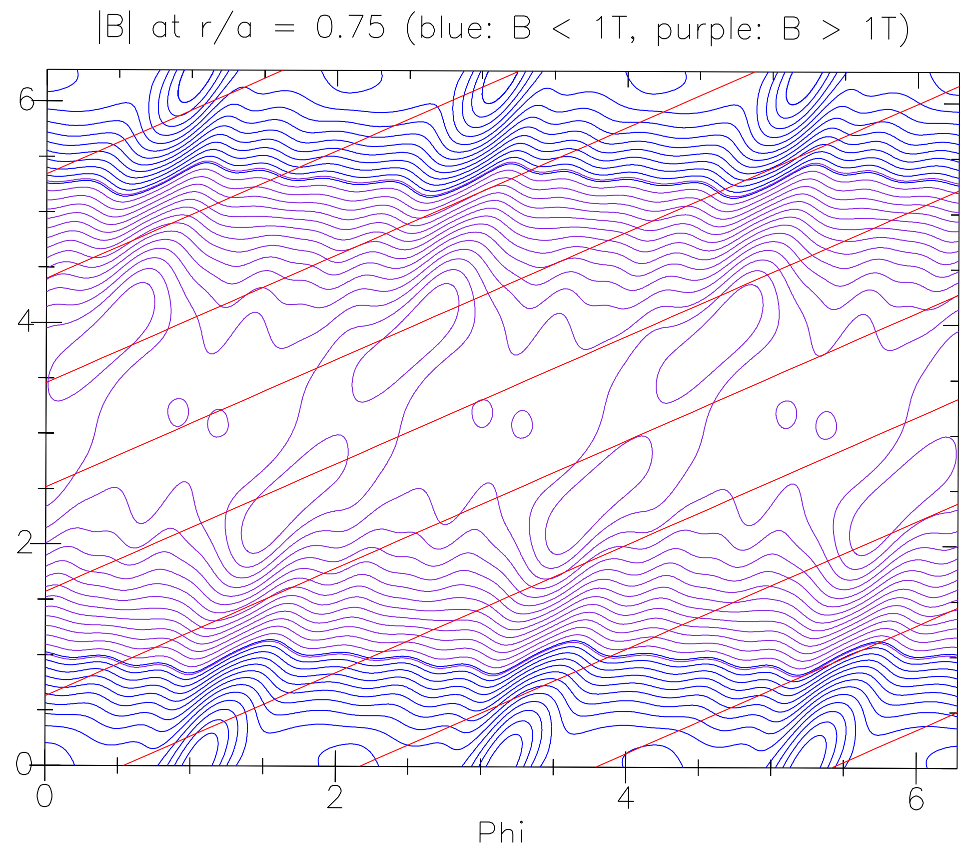


QA Stellarator



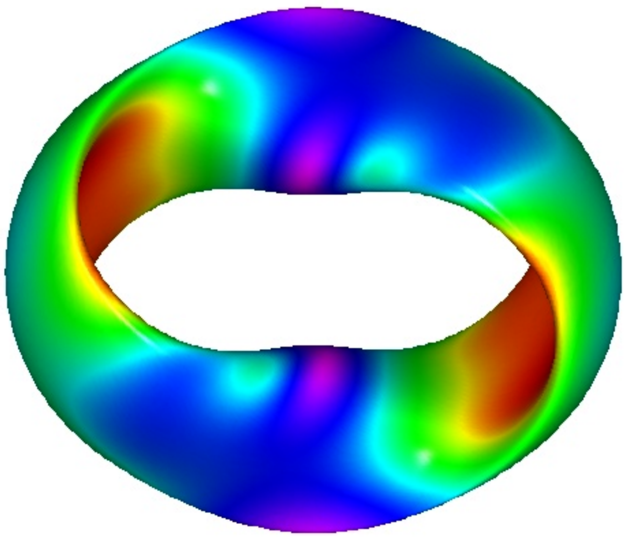
NCSX Uses Quasi-Toroidal Symmetry

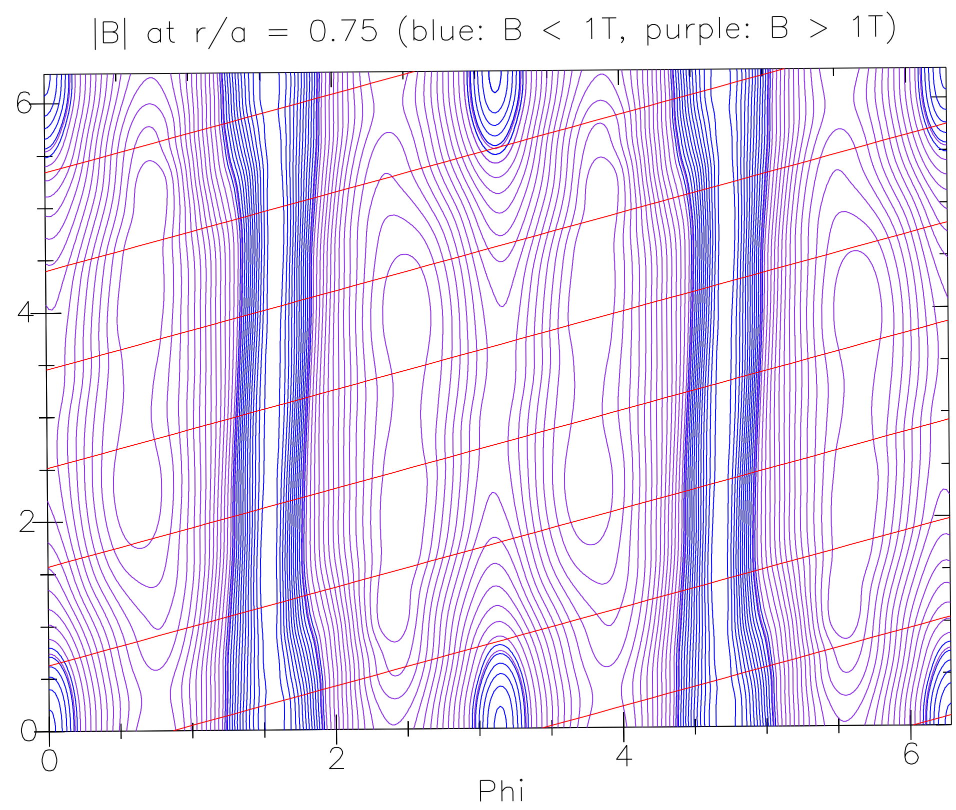




- Combines compactness of a tokamak with low-current steady state properties of a stellarator
  - NCSX will test the physics of tokamak-like confinement, stable pressure limits, ability to avoid disruptions

QPS Uses Quasi-Poloidal Symmetry

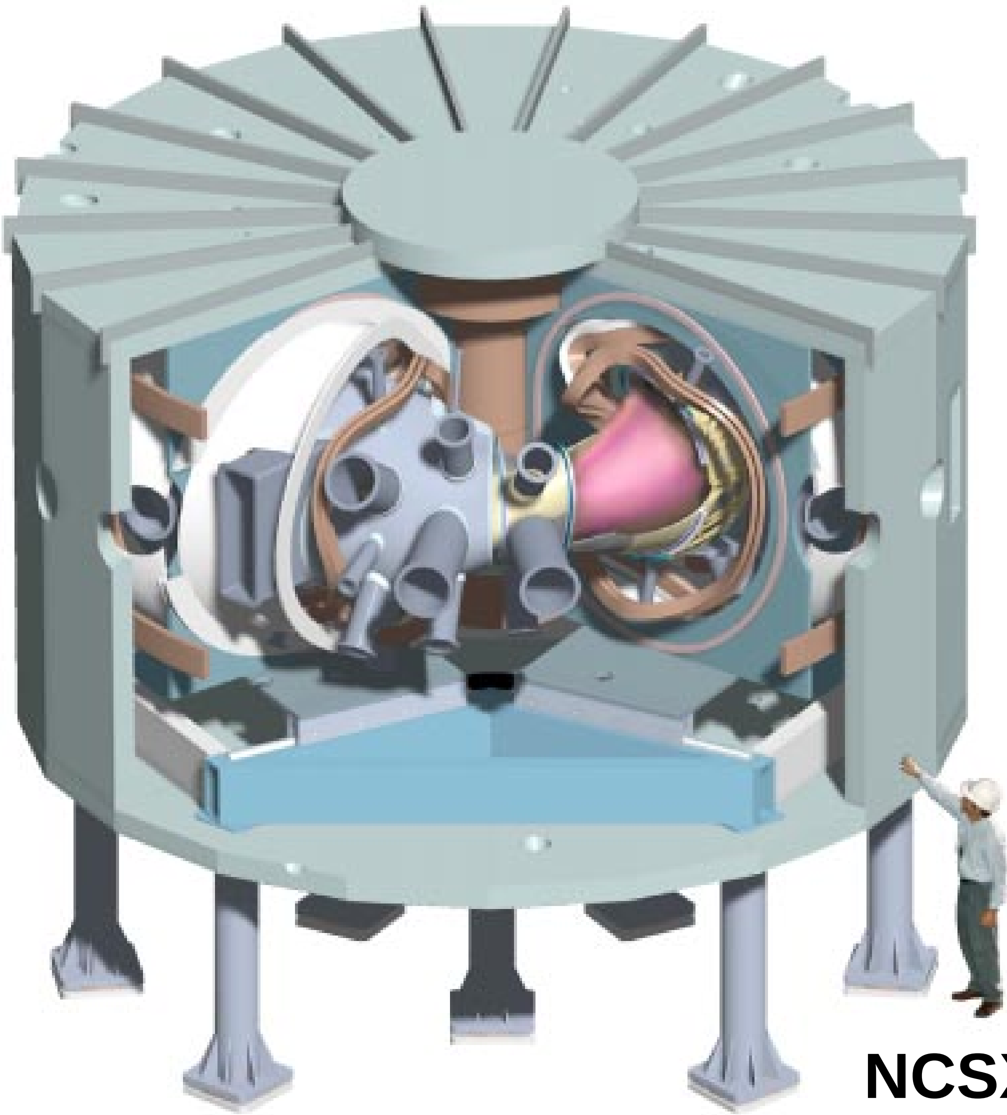




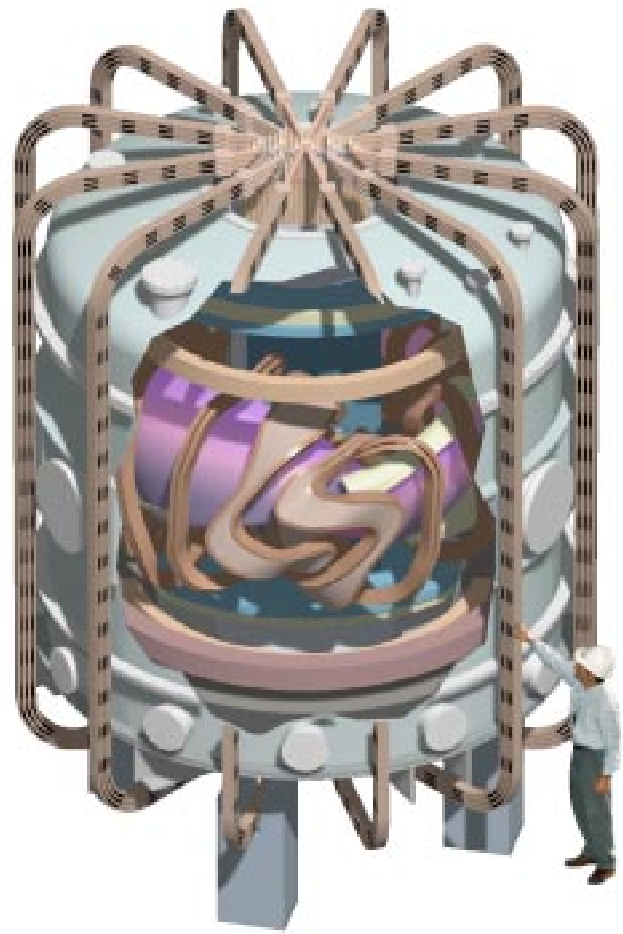
- **Designed to test physics advantages of quasi-poloidal symmetry**
  - **poloidal rotation, much improved confinement, higher stable pressure limits, less change with plasma pressure**

NCSX and QPS Use Different Design Approaches

NCSX uses cryogenic coils and an interior vacuum vessel

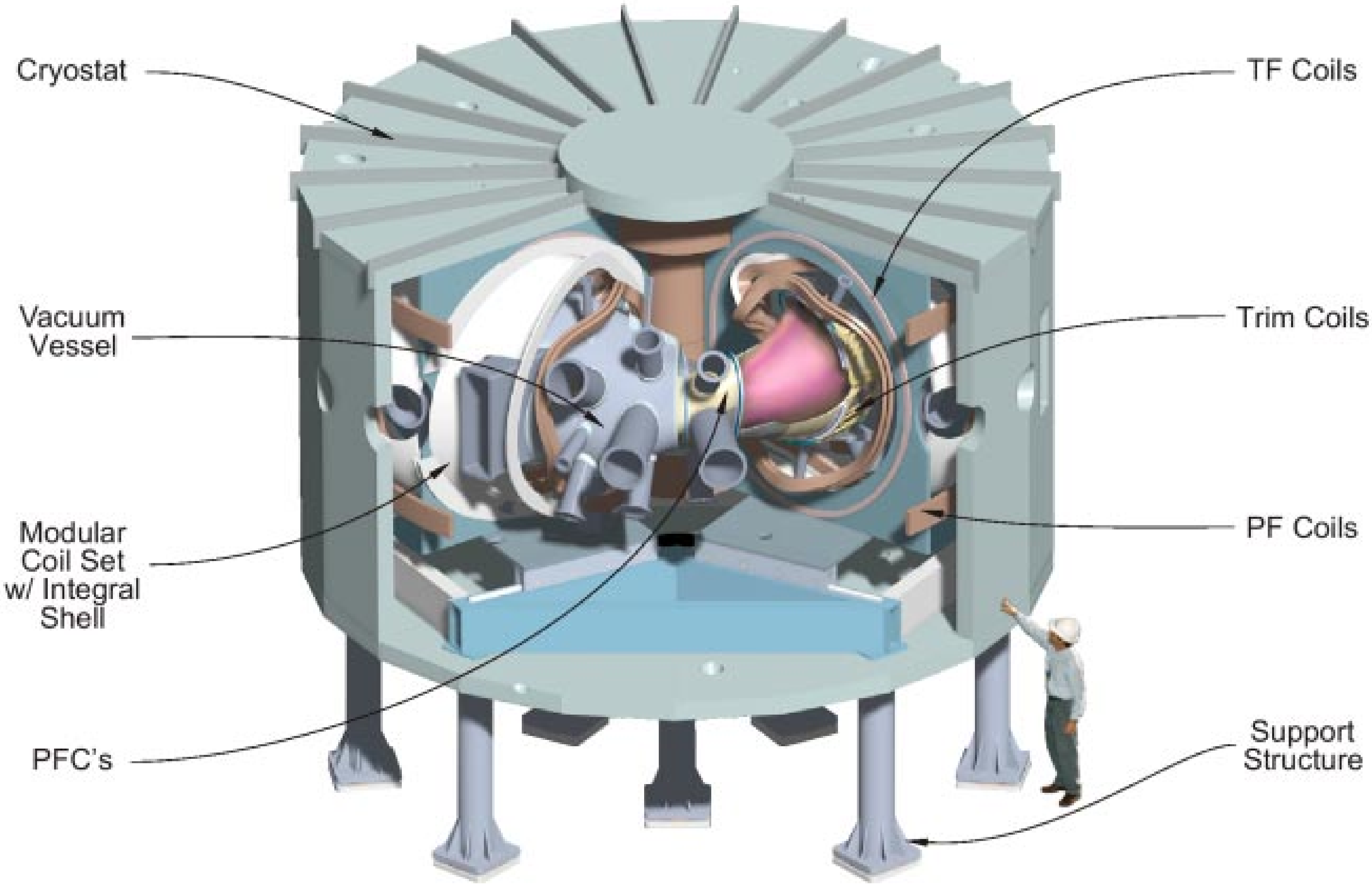


NCSX



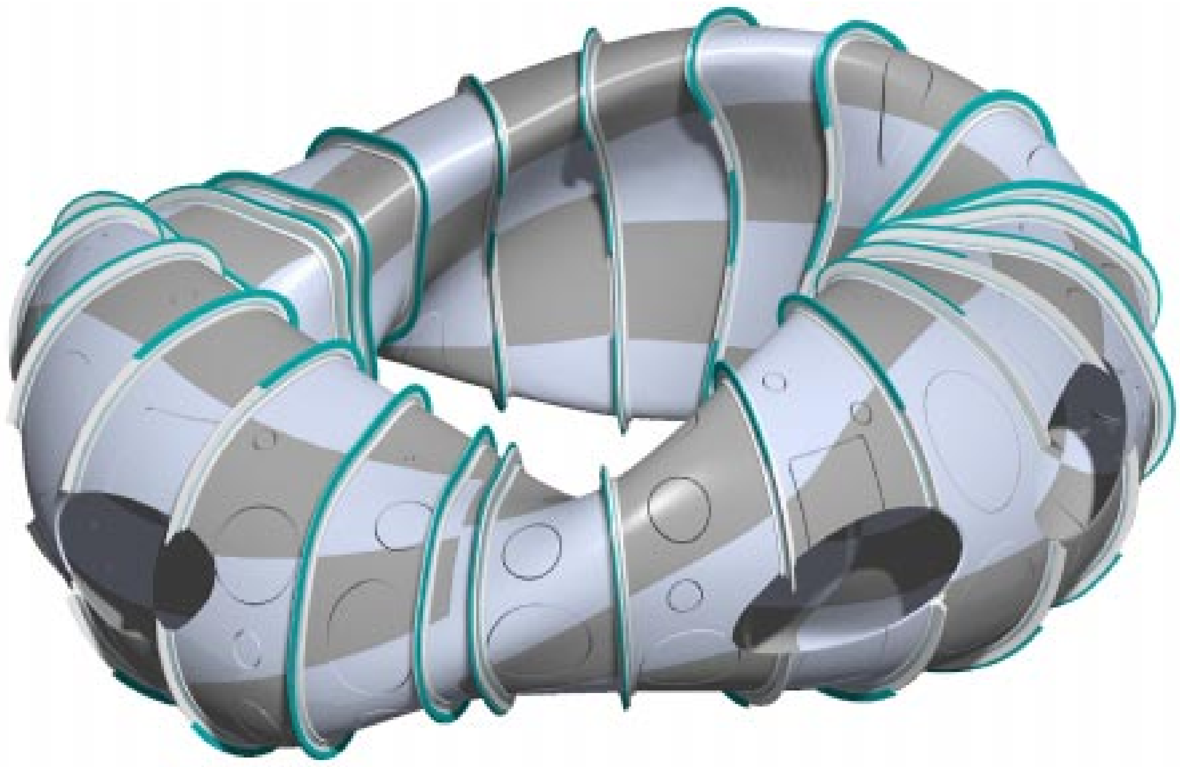
Q PS

NCSX



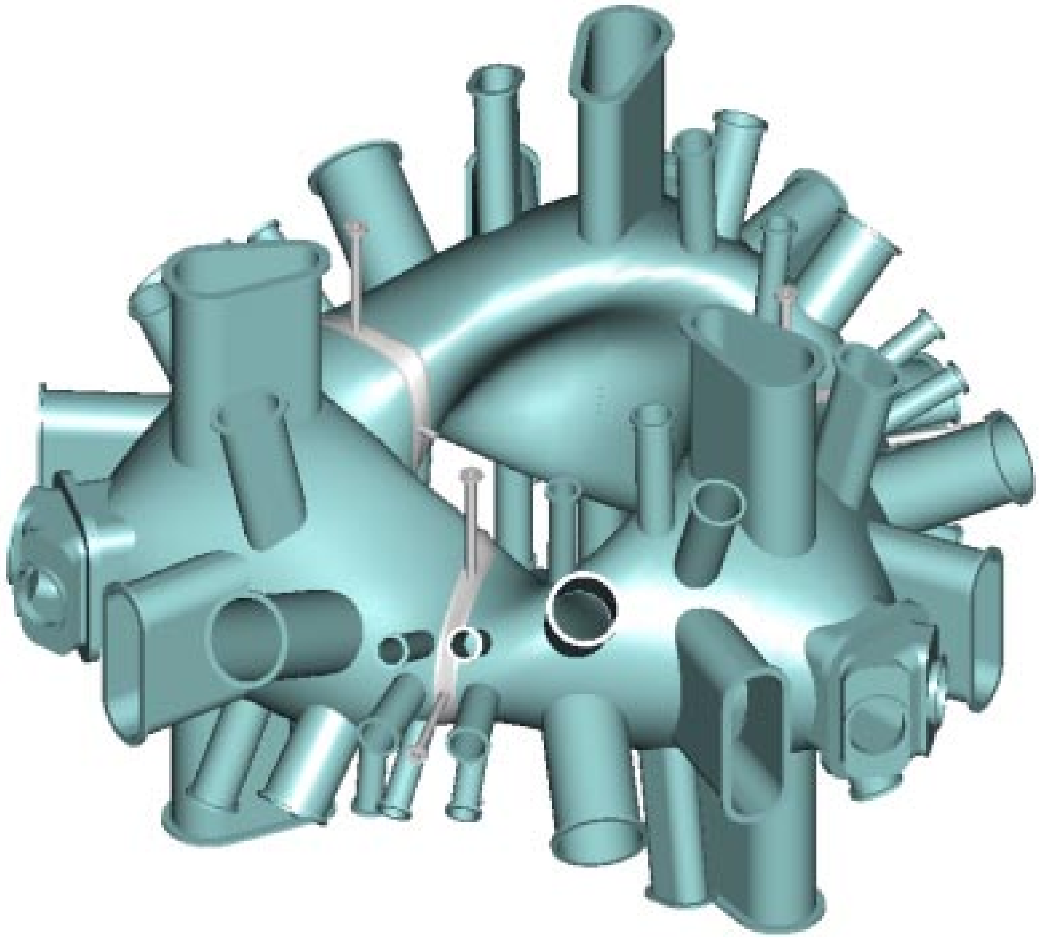
Sited at PPPL; ORNL partner; Project cost ~$70M (Operate March, 2007).

Plasma-Facing Liner



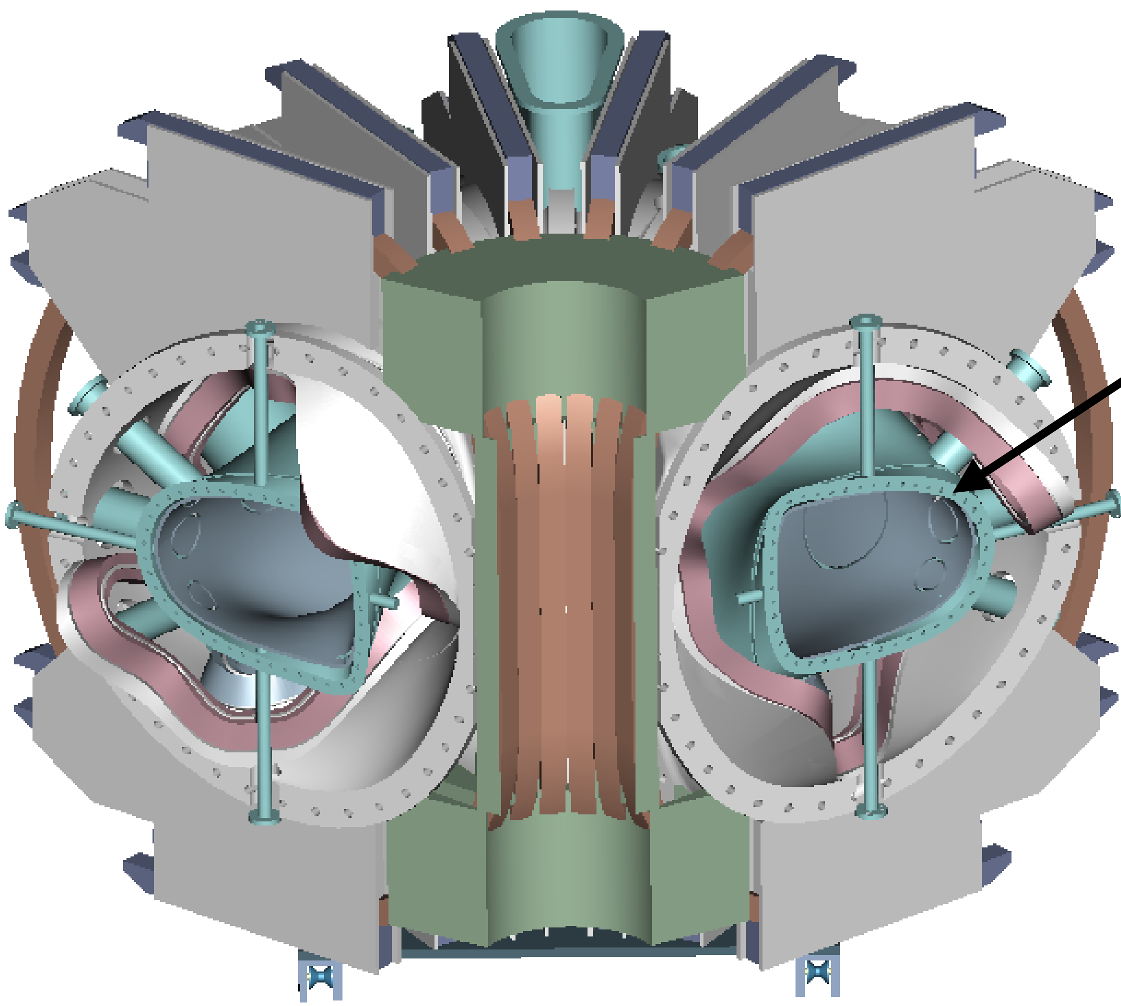
- Full coverage provided by mounting molded carbon fiber composite (CFC) panels on poloidal ribs
  - Panel size ~ 60 cm square, 1 cm thick
- Ribs are separately cooled / heated with He gas for bakeout (350C) and normal operation

Vacuum Vessel



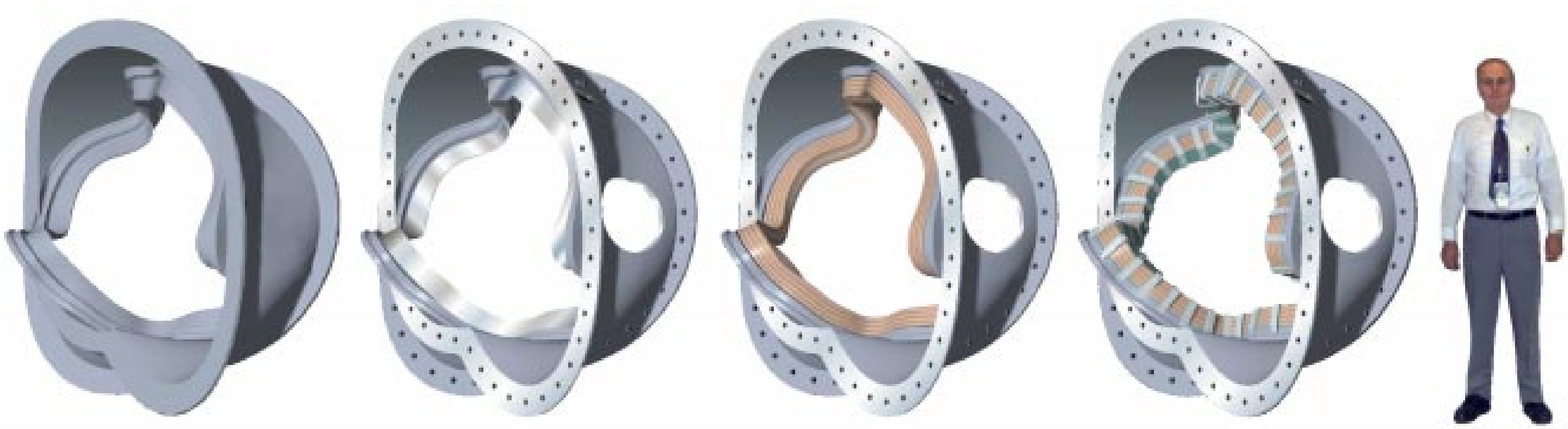
- Inconel 625, thickness 3/8 inch, weight ~ 12000 lbs
- 90 ports, bolted joints connect three sections
- Traced with He gas lines for heating (to 150C) and cooling
- Thermal insulation between vacuum vessel and cold coils

The Vacuum Vessel Must Fit Inside the Modular Coil Set



Modular Coil Manufacturing Sequence

- **Continuous support for strength and accuracy of windings**
- **Shell segments repeat 6 times**



Rough casting

Features are machined

Conductor wound directly into structure

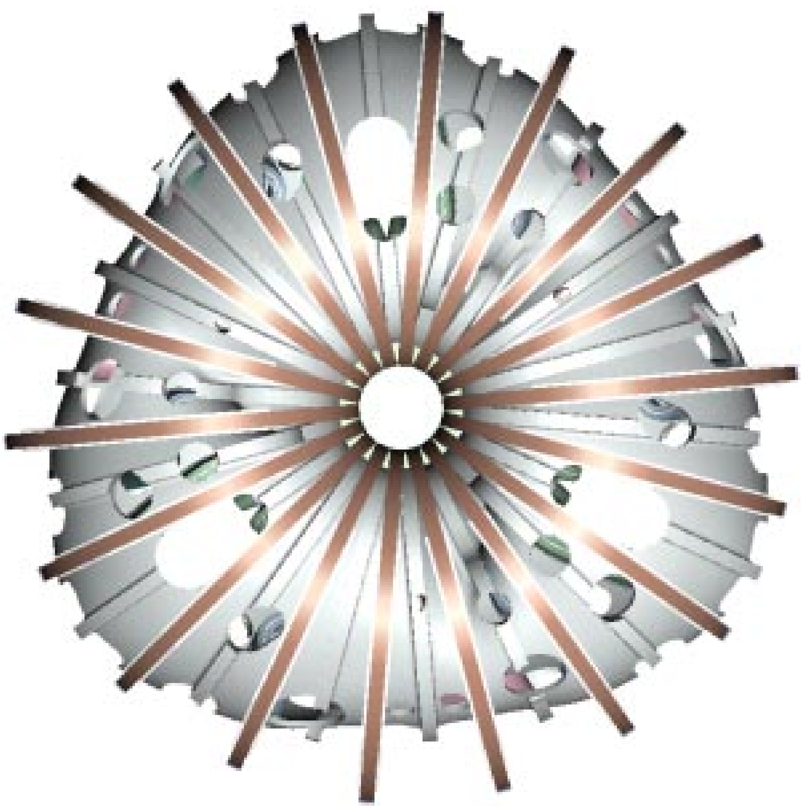
Auxiliary support clamps are installed

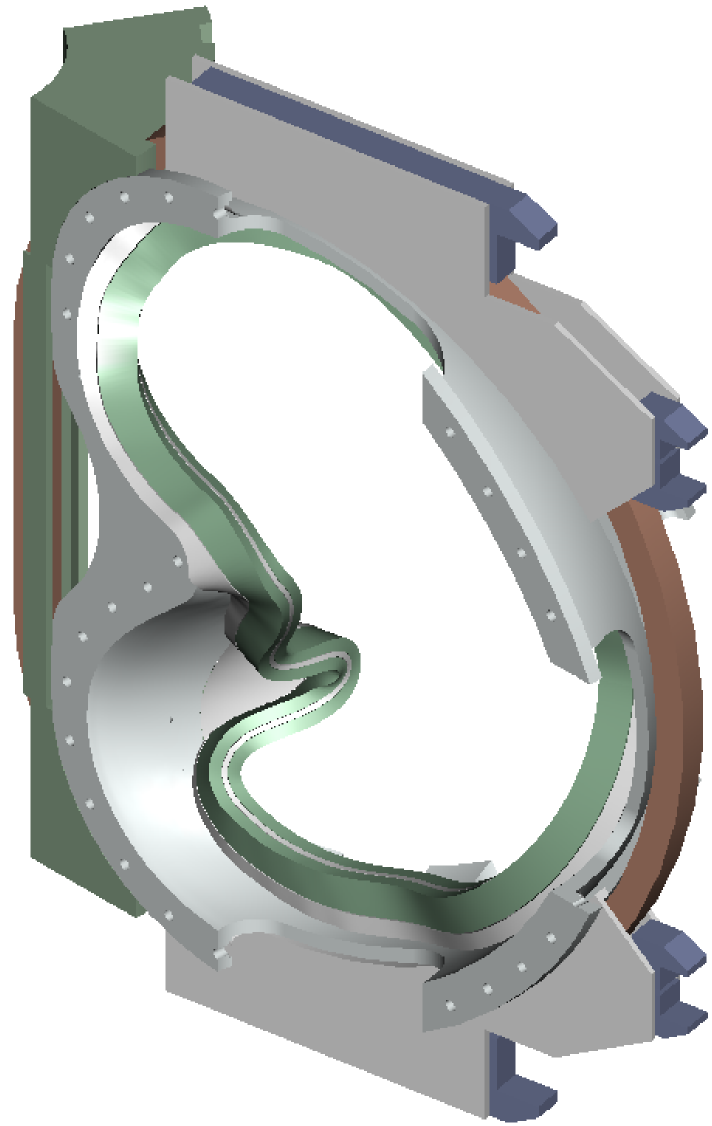
Shell Covers Modular Coils

- Consists of individual modular coil forms that are bolted together
- Penetrations for access are provided wherever needed

Toroidal Field Coils

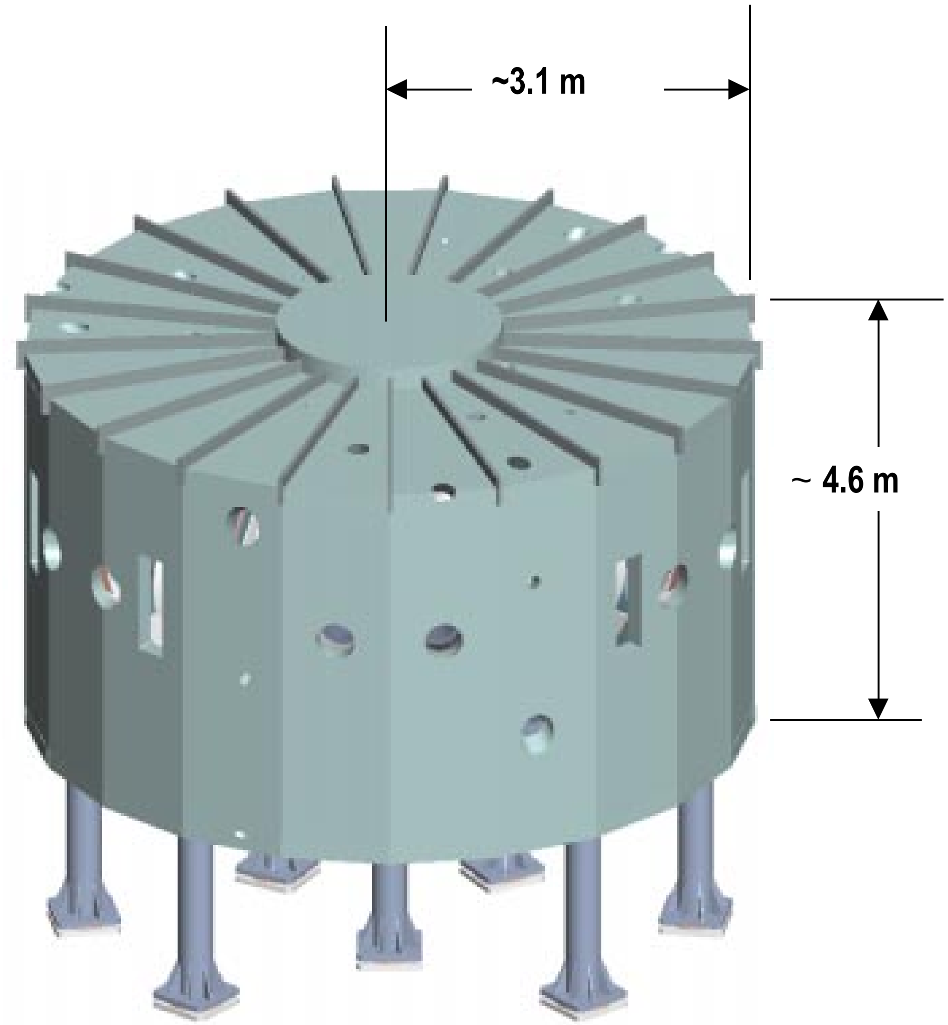
- 18 coils provide additional field
- Supported from modular coil shell
- Wound from hollow copper conductor
- Pre-cooled to LN_2 temperature (like modular coils)



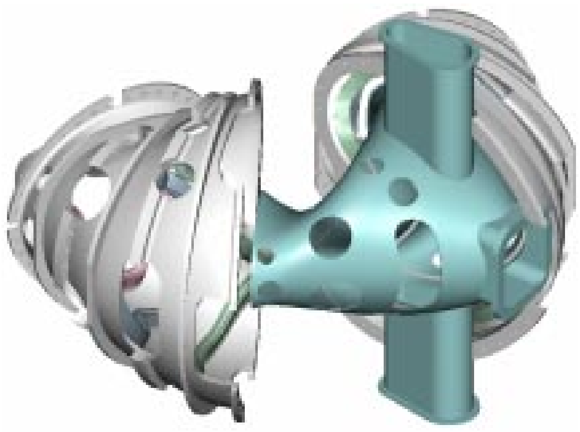


Cryogenic Coils Enclosed in a Cryostat

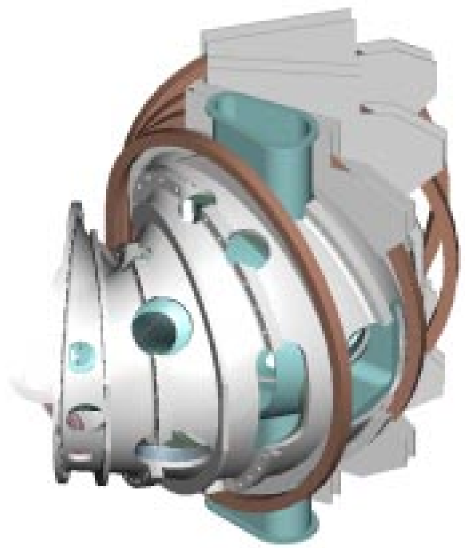
- **Cryostat uses substructure sprayed with urethane foam**
- **Holes provided for all vacuum vessel port extensions**
- **Silicon rubber boots to seal between vessel port extensions and cryostat**
- **8” thickness reduces heat leaks to air but still will require local heaters/blowers to avoid condensation**



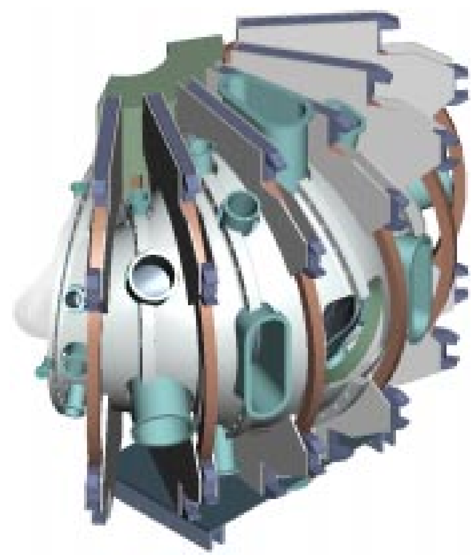
Coils and Vacuum Vessel Are Pre-assembled in Field Periods



Rotate modular coils over vacuum vessel period

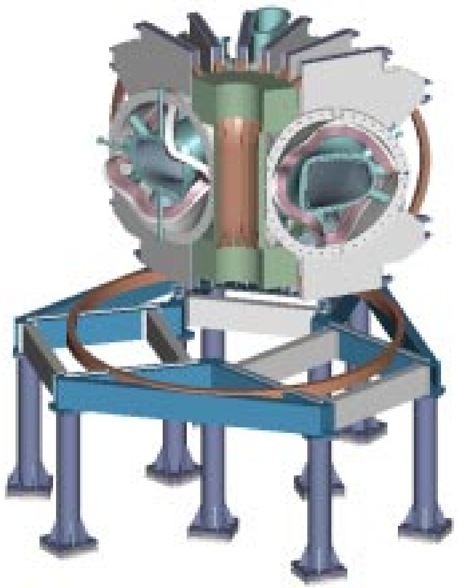


Add TF coils and out-of-plane support structure



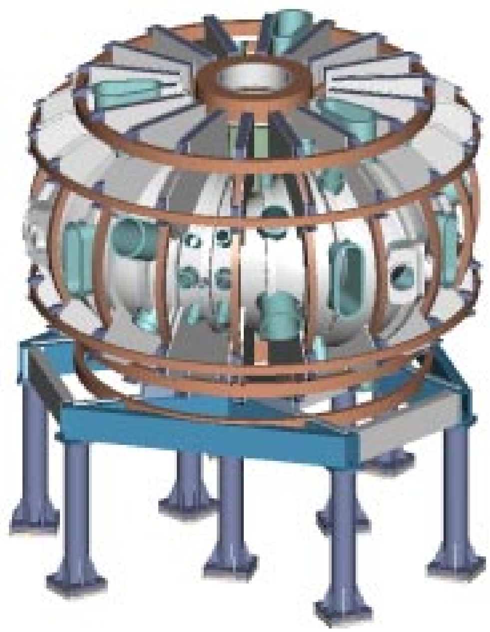
Add vacuum vessel port extensions to complete field period sub-assembly

Field Periods Are Assembled on Machine Structure



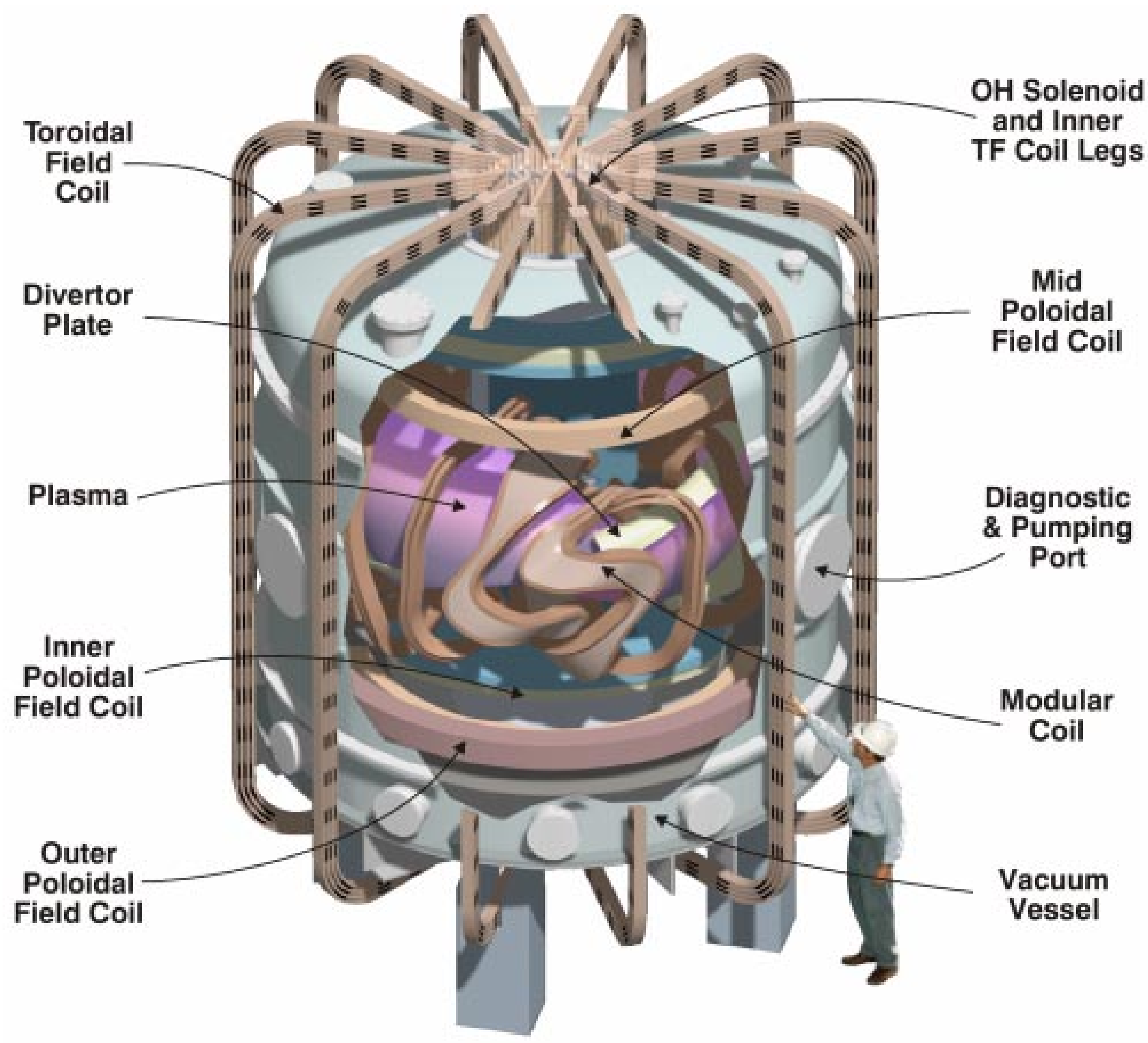
Field period lowered onto machine base in position ~ 500 mm radially outward

3 field periods in position prior to radial assembly step



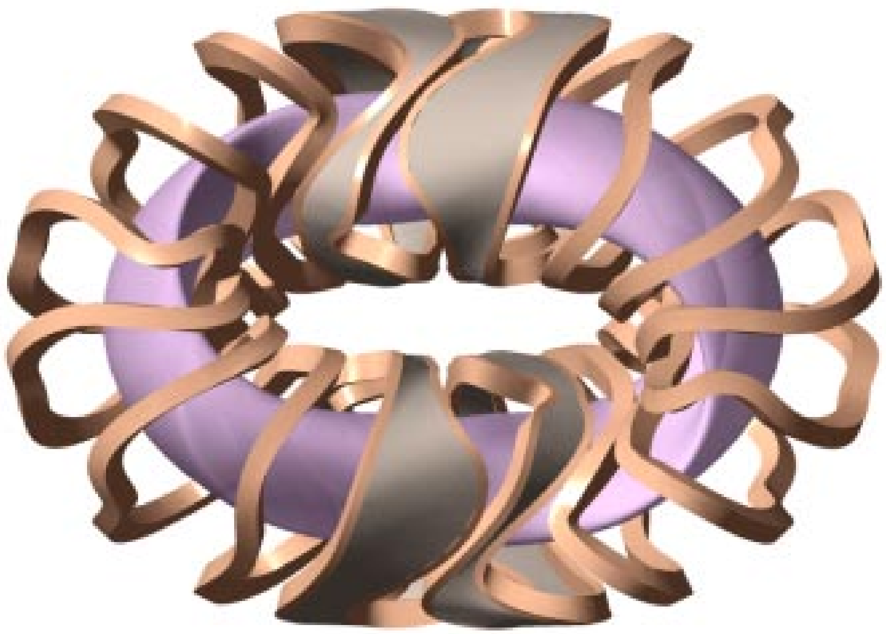
Field periods connected after radial motion, PF coils raised/lowered into position

Quasi-Poloidal Stellarator



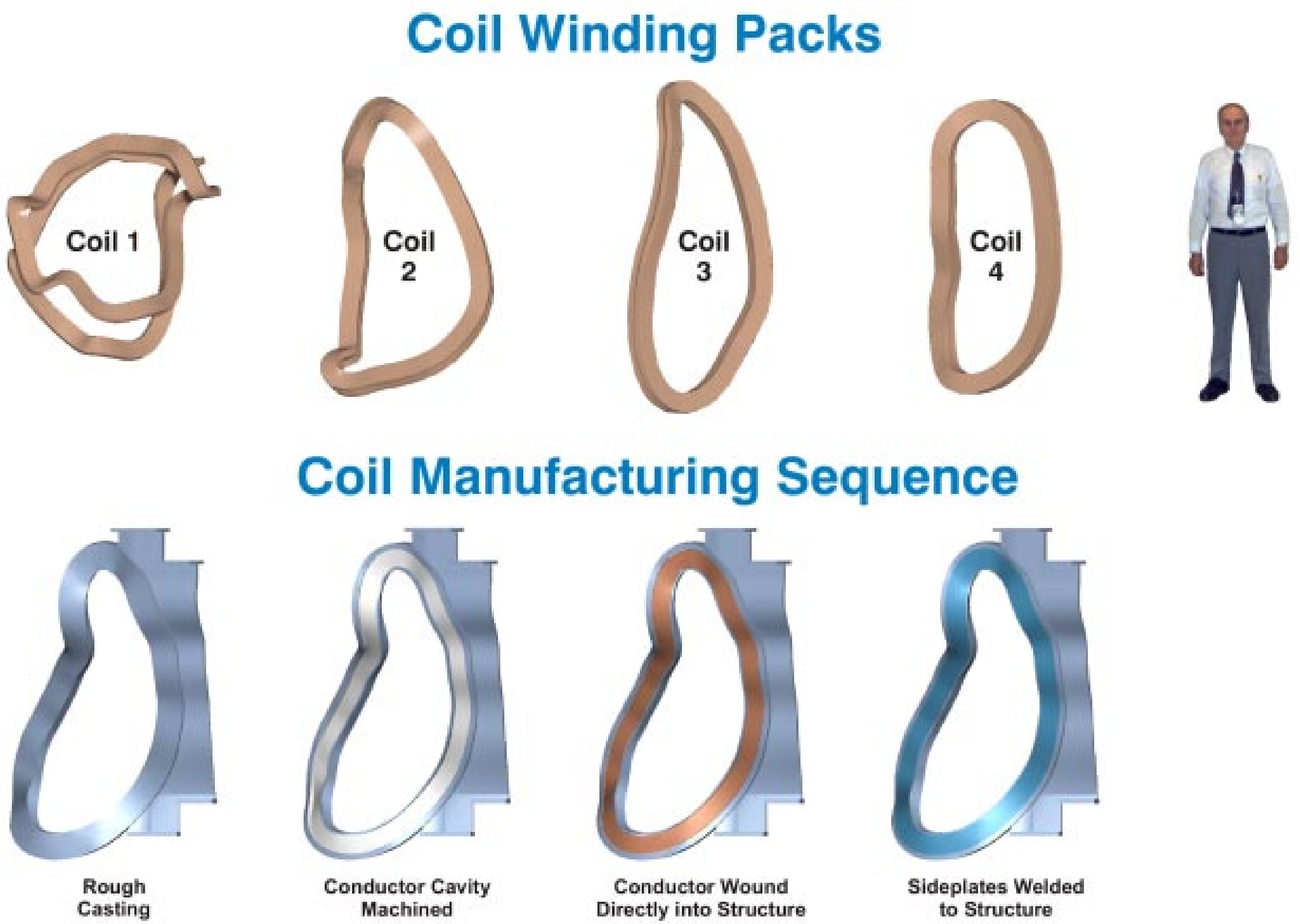
The QPS Plasma and Coil Configuration

TOP VIEW

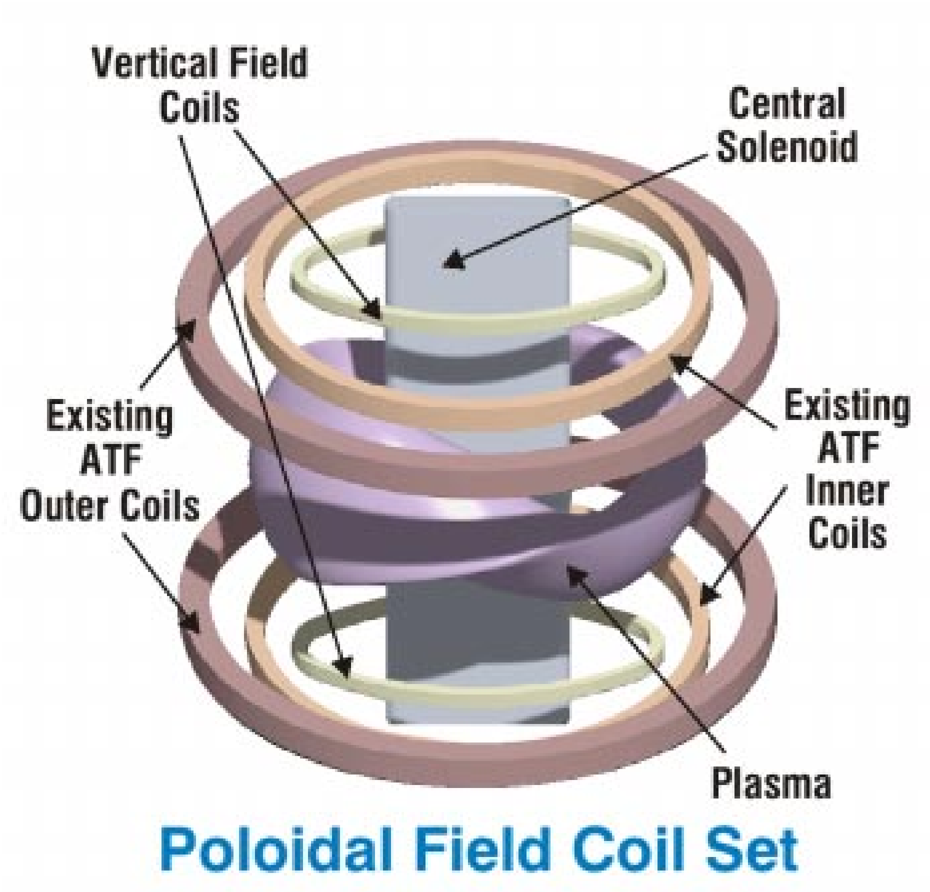


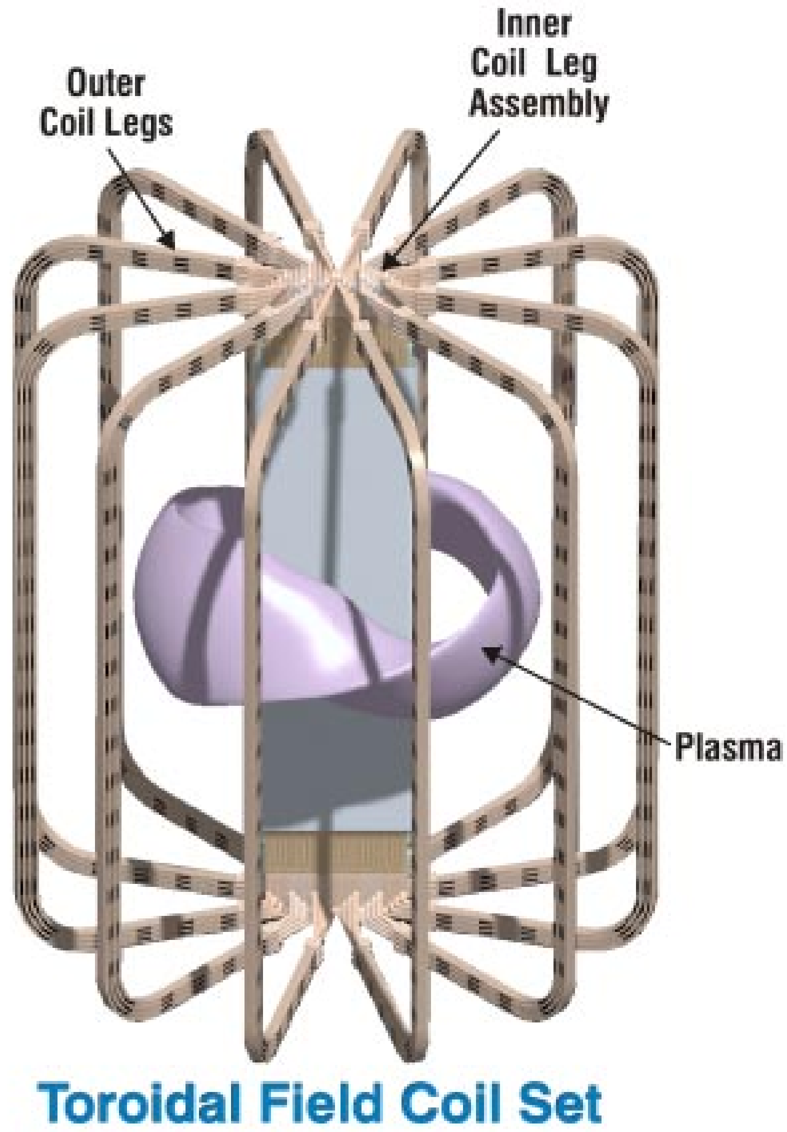
SIDE VIEW

The QPS Modular Coils

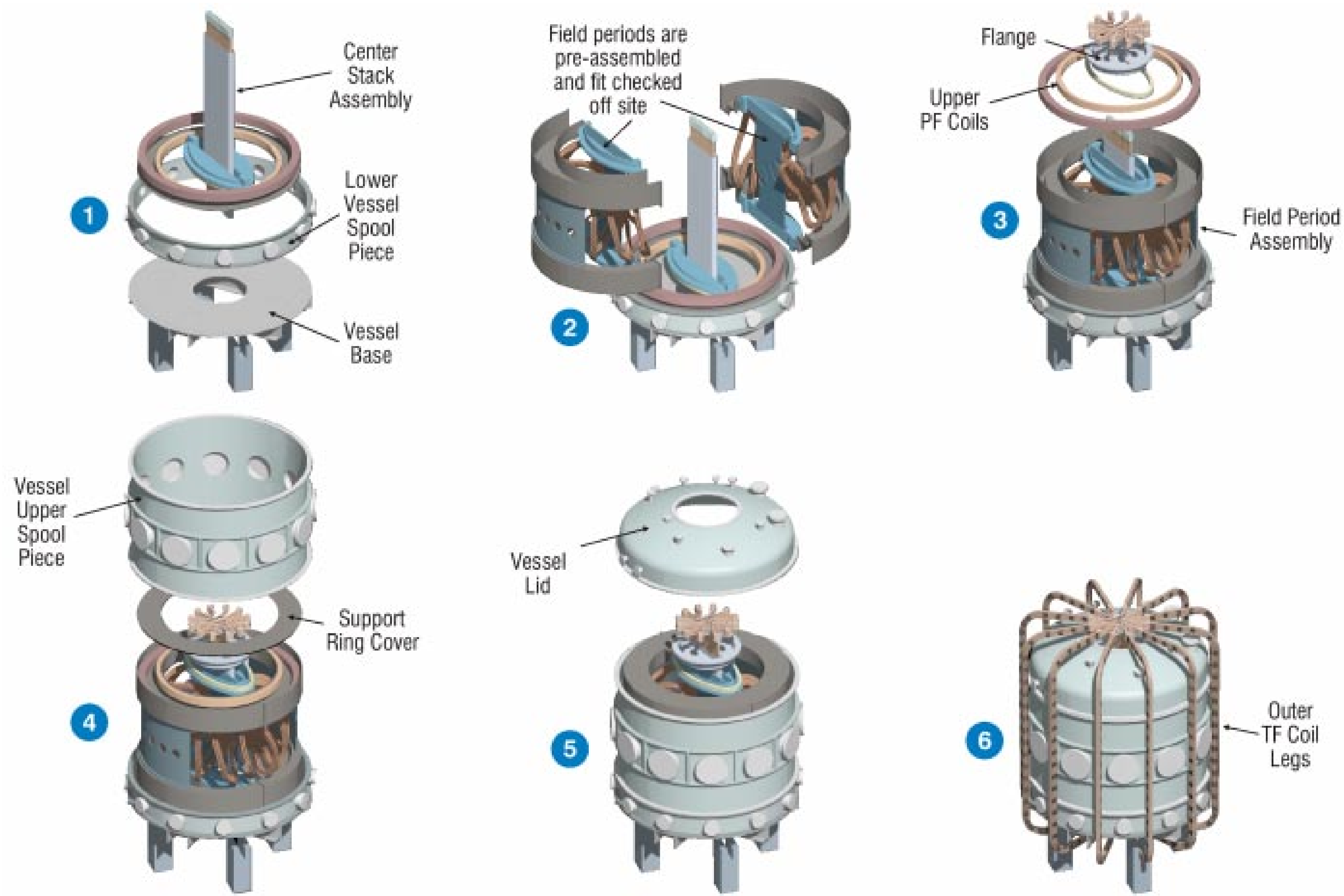


QPS Also Has Auxiliary Coil Sets for Flexibility





QPS Assembly Sequence



Vacuum Considerations

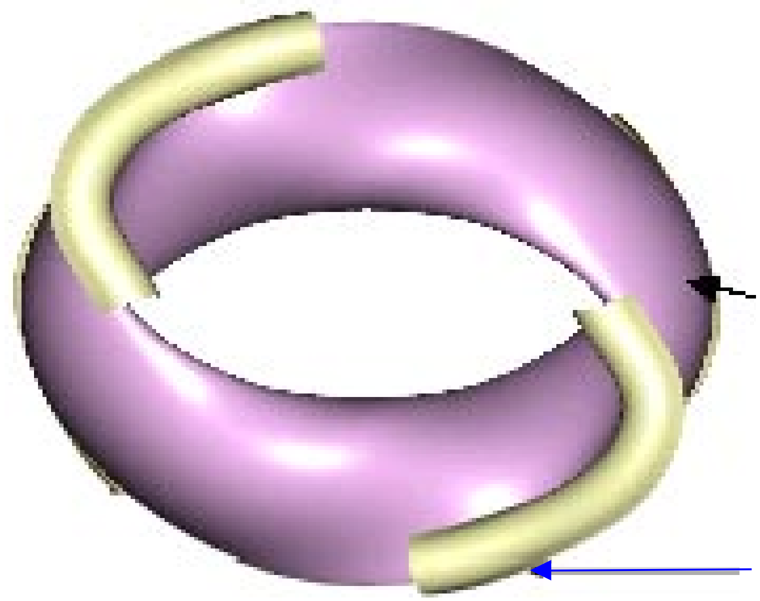
- High vacuum quality is needed for fusion experiments
  - typical plasma densities correspond to 1,000,000 of atmospheric density
  - need gas density around plasma a factor of 10,000 times smaller than this
  - volume of gas region around plasma 2 x plasma volume for NCSX and ~20 x for QPS
- Consequences of poor vacuum conditions
  - gas neutrals enter the plasma and cause loss of energetic ions and radiate energy
  - metal impurities sputtered from the wall enter the plasma and radiate energy
  - lose control of the plasma density, cools plasma
- Methods of maintaining good vacuum properties
  - reduce volume of gas around plasma: NCSX has close-fitting vacuum vessel
  - high pumping speed: pumps or bury gas in liquid metal pumping surfaces
  - clean plasma-facing surfaces: bake at high temperature to drive off adsorbed gas
  - clean other surfaces in vacuum tank with plasma glow discharge
- Unique problem for QPS -- maintaining high vacuum in large tank with large internal surface area

Control of Neutrals

- The QPS vacuum vessel is a bell jar with a volume of ~ 45 m^3; it provides a large reservoir for neutral gas which can have a major effect on density control

The build-up of neutral pressure in the vessel will be minimized through local concentration of recycling

- Magnetic field lines (particles) leave the plasma predominantly at localized places
- There recycling neutrals will be confined mechanically by baffles and be re-ionized by the boundary plasma.



Other Vacuum Control Issues

Control of plasma density

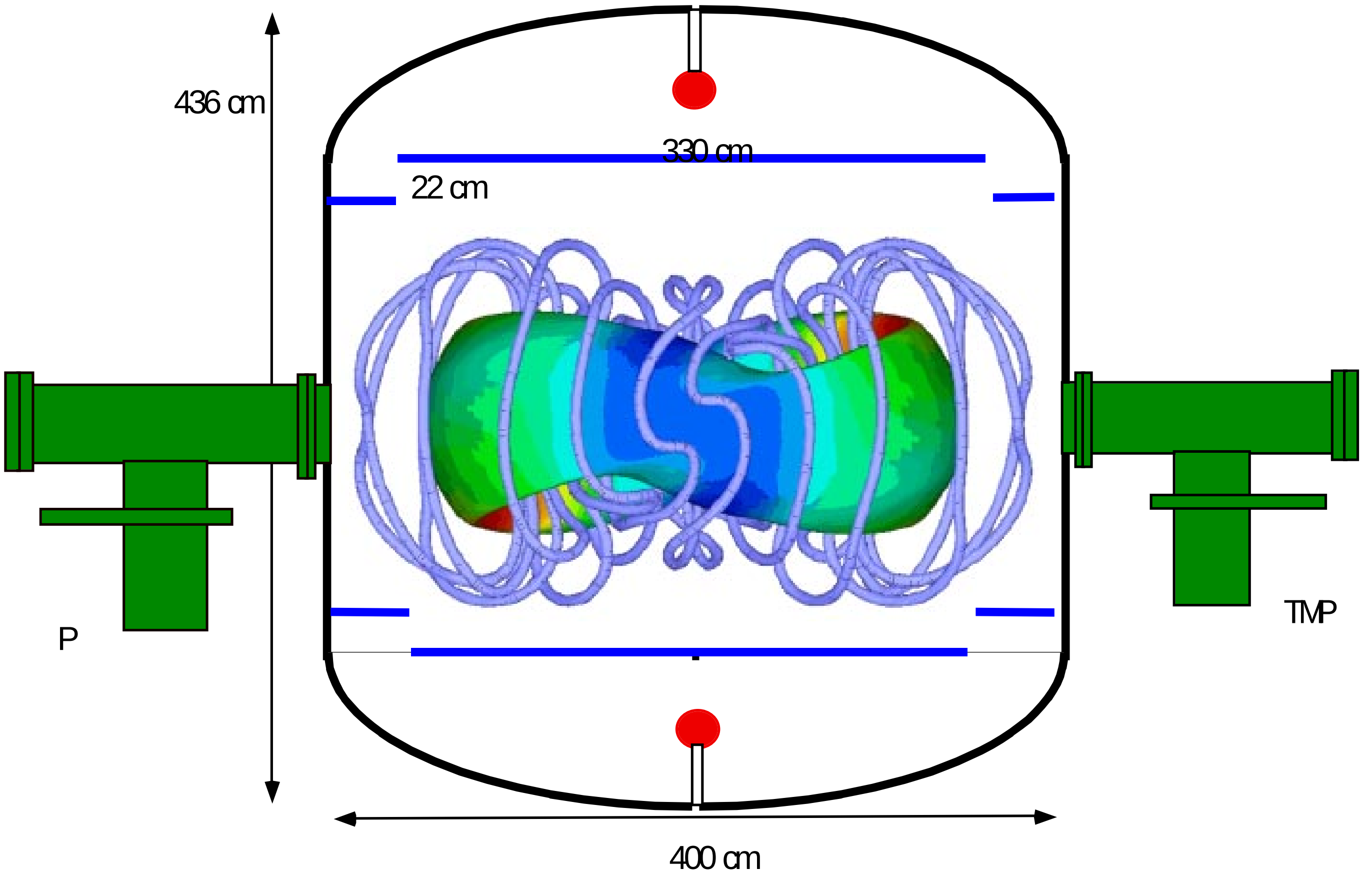
1. Recycling control through surface pumping via boronization of all plasma-facing components
2. Large-area titanium (or cryo-) pumping of neutral gas
3. Direct fueling of the core plasma with gas injectors at the divertor baffles

Control of impurities

1. Wall conditioning: baking, glow-discharge cleaning and thin-film deposition (e.g. boronization)
2. Control of plasma-surface interactions: optimize materials choice (C, B_4C), location, shape, conditioning
3. divertor plasma between baffle surface and plasma surface will help shield main plasma from impurity source
4. Leaks in coil casings: gas cooling will make leaks more benign and will help to diagnose leaks

QPS Solution

- Low base pressure in vacuum vessel with turbo-molecular pumps
  - 4 x 10^{-9} Torr (stainless steel outgassing rate = 9.6 x 10^{-6} TorrL/s, pumping speed = 5000 L/s, leak rate = 10^{-5} TorrL/s with metal seals and double viton seals baked at 150 C and differentially pumped
- High Titanium gettering pumping speed (including conductance)
  - 4.6 x 10^{5} L/s (for both hydrogen and oxygen)



Hybrid Solution Possible for QPS?

- Easier to maintain high vacuum with internal vacuum vessel (NCSX)
- Easier to construct, more flexibility with external vacuum vessel (QPS)
- Partial interior vessel with open areas could have benefits
  - protects the coils from the direct energetic flux of the plasma that can knock off adsorbed gas, allowing lower temperature epoxy for the coils
  - can be heated to prevent gas from accumulating on the plasma facing surface close to the plasma
  - can reflect neutrals back into the plasma so a significant part of the recycling can occur near the plasma rather than from the large reservoir of the vacuum tank
  - can help contain the gas puff during the initial plasma buildup rather than filling the whole tank
  - much cheaper and easier to install than a high-vacuum liner and need not be as accurate
- Best of both approaches or worst?

Status and Plans

- Successful DOE reviews were held in April and May 2001 for both NCSX and QPS
- Further improve the plasma and coil properties
- Complete assessment of physics properties
- Assess flexibility obtained with different coils
- Improve engineering design and cost/schedule estimates
- DOE Design, Cost & Schedule Reviews
  - NCSX May 2002 and QPS April 2003
- 2003-2007: R&D, design and construction
- Operation in 2007: March (NCSX), Sept. (QPS)