Overview of the National Compact Stellarator Experiment

Casting The Way to a New Energy Source

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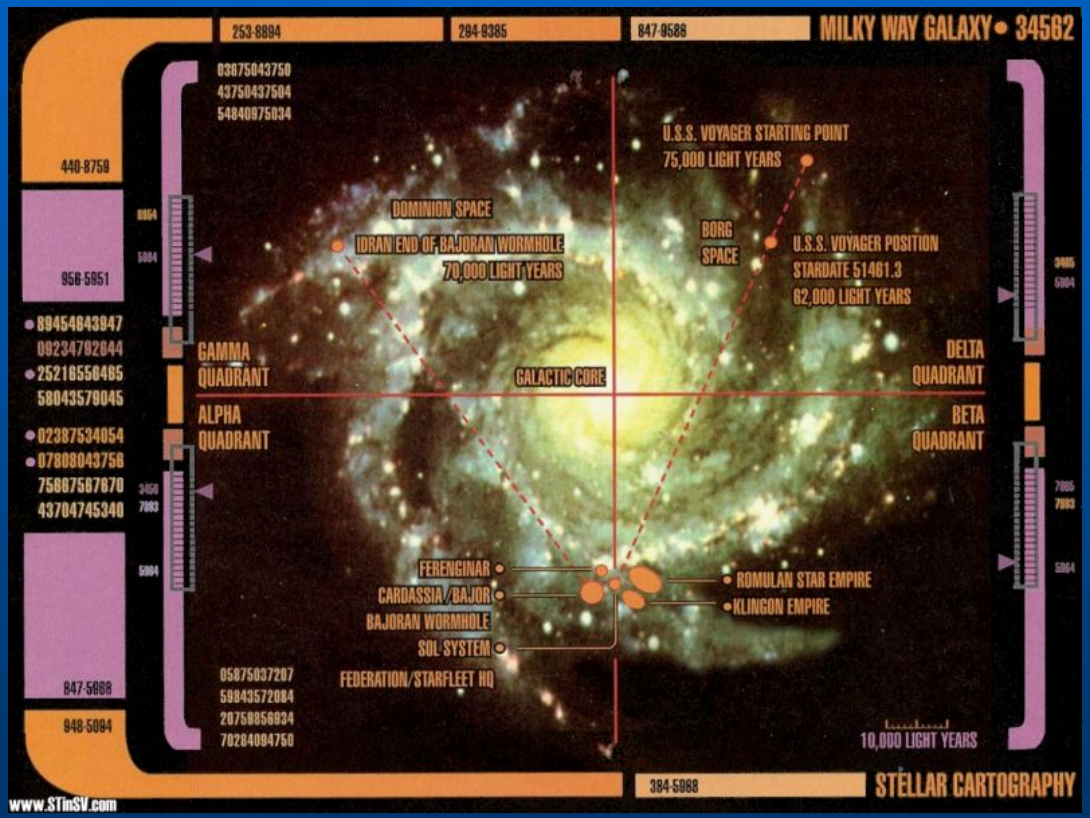
Outline

- Fusion Fundamentals
- Why the Interest in Stellarators
- Overview of the National Compact Stellarator Experiment Project
- Summary

Fusion: The Power Source of the Stars

- Fusion works! The sky is filled with stars, each of which is a fusion reactor
- The tremendous energy produced in stars is the result of the conversion of mass into energy by fusion.



Files used courtesy of Star Trek in Sound and Vision" (http://www.stinsv.com/

$E=mc^2$

- The basic formula for understanding how fusion works.
- When the nuclei of two light atoms are forced to fused together, the resulting nucleus has less mass.
- The “missing” mass is converted to energy.
- Nuclei are positively charged, and therefore the two nuclei repel each other.
- A tremendously high speed collision between the nuclei is necessary for fusion to occur.
  - The nuclei need to be forced together at a sufficiently high speed (temperature) so that they don’t merely bounce off of each other, but they collide and fuse.

FOR MORE INFO...

Visit www.pppl.gov and www.ofe.er.doe.gov.

What is Plasma?

- Plasma is the fourth state of matter.
- 99% of the visible universe is plasma!
- An atom contains an equal number of negatively charged electrons orbiting a nucleus consisting of an equal number of positively charged protons and one or more neutrons which have no charge.
- An ordinary gas is a collection of electrically neutral atoms.
  - A gas can be changed into a plasma by heating it sufficiently to cause the electrons to escape from the atom.
  - The result is a gas containing negatively charged electrons and positively charged ions.

How Plasmas Behave

- Unlike an ordinary gas, they are good conductors of electricity.
- They are strongly affected by electromagnetic forces.
- They can generate electromagnetic forces.

These self-generated forces resulting from the collective motions of charged particles and electrical currents result in tremendously complex behavior that even after more than 50 years of research are still incompletely understood.

(Ref.: Fusion Energy Science brochure; C. Baker, editor; USDOE; January, 2001)

The Most Promising Magnetic Fusion Concepts

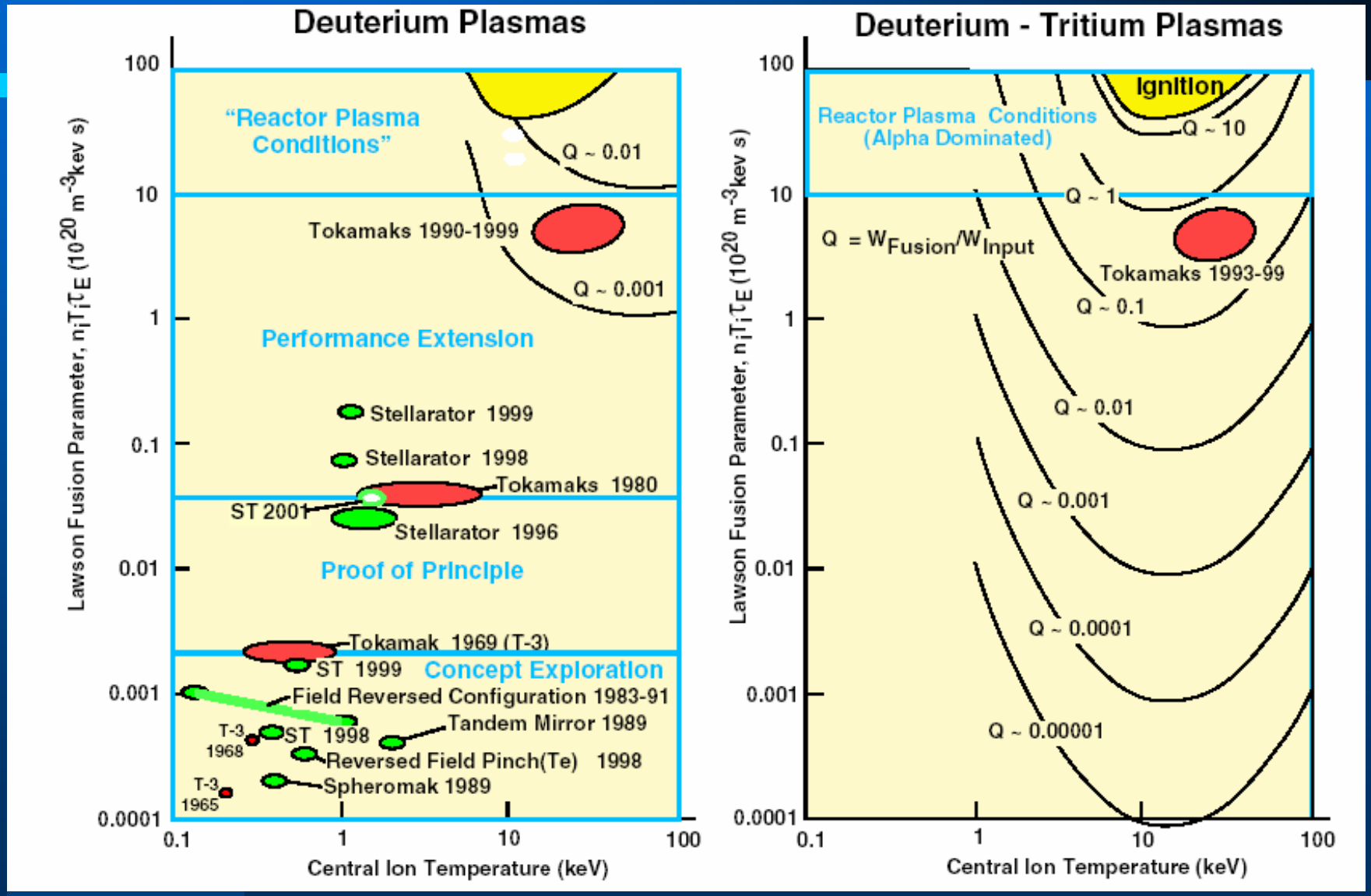
- **The Tokamak,** the "frontrunner". Has been the workhorse of the fusion program, and is responsible for much of the progress in fusion. Major deficiency: plasma confinement relies on high current flowing in the plasma.
  - *To date it has not been possible to operate at the high performance parameters required for practical power production for more than a few seconds without the plasma current becoming unstable and breaking down (disrupting).*

- **The Spherical Torus,** coming up fast.

- **The Stellarator**, actually one of the first concepts for MFE. A pure stellarator does not have a plasma current, and therefore is inherently steady state. Didn't confine plasmas very well in the early days, but this problem has been solved with the help of advanced computational capability. Major deficiencies: pure stellarators have a large major diameter (i.e. high cost) and are not as well developed as the tokamak.

  - **The Compact Stellarator.** NCSX is the first of a new breed of stellarators called compact stellarators. They are a hybrid of a tokamak and a stellarator. They use 3-D field shaping in conjunction with a relatively modest plasma current to confine the plasma. Its promise is that it will bring together the best features of the tokamak and the stellarator and produce a magnetic fusion energy concept that will operate at high performance in steady state in a more compact stellarator.

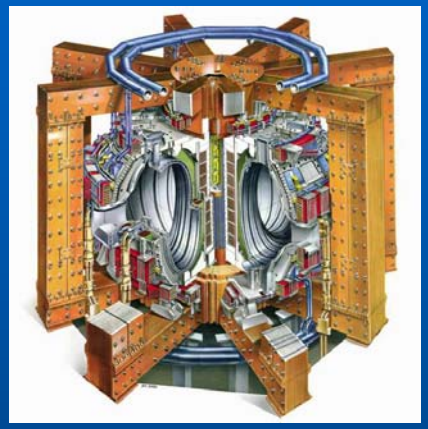
Fusion's Achievements To Date



Appreciable Fusion Energy Production Has Been Demonstrated

TFTR

- The Joint European Torus (JET) in Cullham, England was the first to achieve a significant release of energy in a controlled nuclear fusion reaction using a Deuterium-Tritium (D-T) fuel mixture.
  - In November, ' 91 about 1.7 MW of fusion power was released for ~1.2 s.
  - In '97 it set a new record of 16.1 MW of fusion power for ~1.4 s.



JET

- The Tokamak Fusion Test Reactor (TFTR) at Princeton was the first do perform extensive research using D-T.
  - In November, '94 , it broke the then current world record and produced a peak 10.7 million watts of fusion power for a period of about 1 s.

…But the energy produced was only for 1-2 sec.!

The challenge:

to devise a reactor that is capable of steady state operation at the high performance parameters needed for competitively priced energy production.

Tokamaks may require elaborate controls to stabilize the plasma so sustained operation is possible.

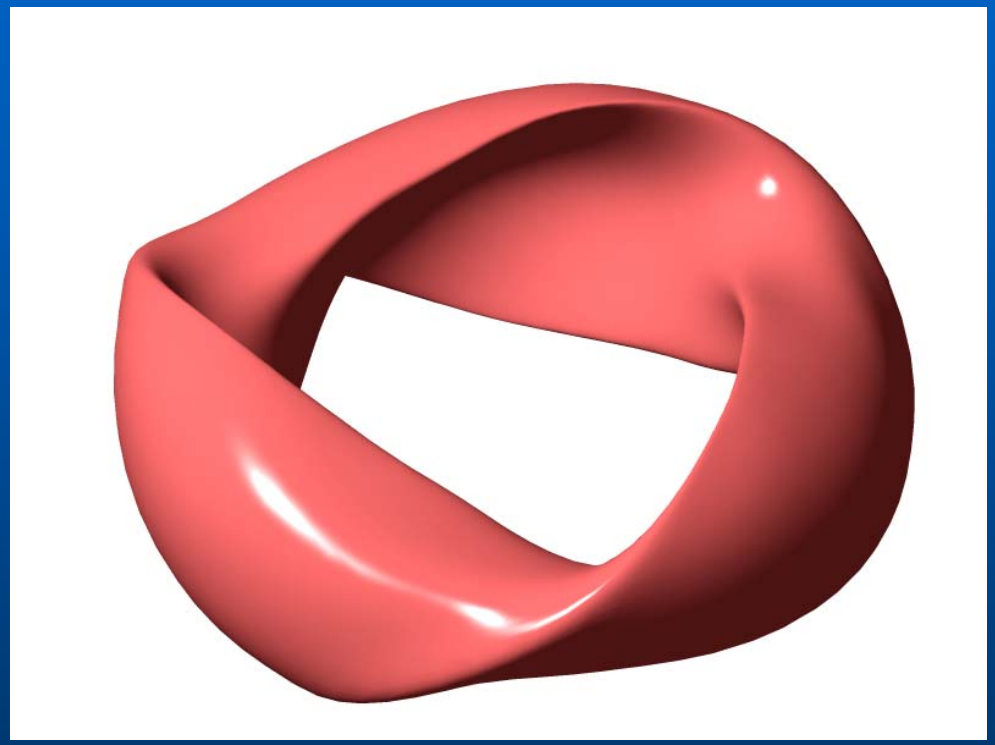
Stellarators May Provide A Better Solution via 3D Plasma Shaping and External Controls

Predicted benefits:

- **Passively stable.**
- **Self-sustained.**
- **Access to new physics.**

Cost:

- **Complex plasma geometry, which means complex machine geometry.**
- **BUT within the state of the art of industry!**



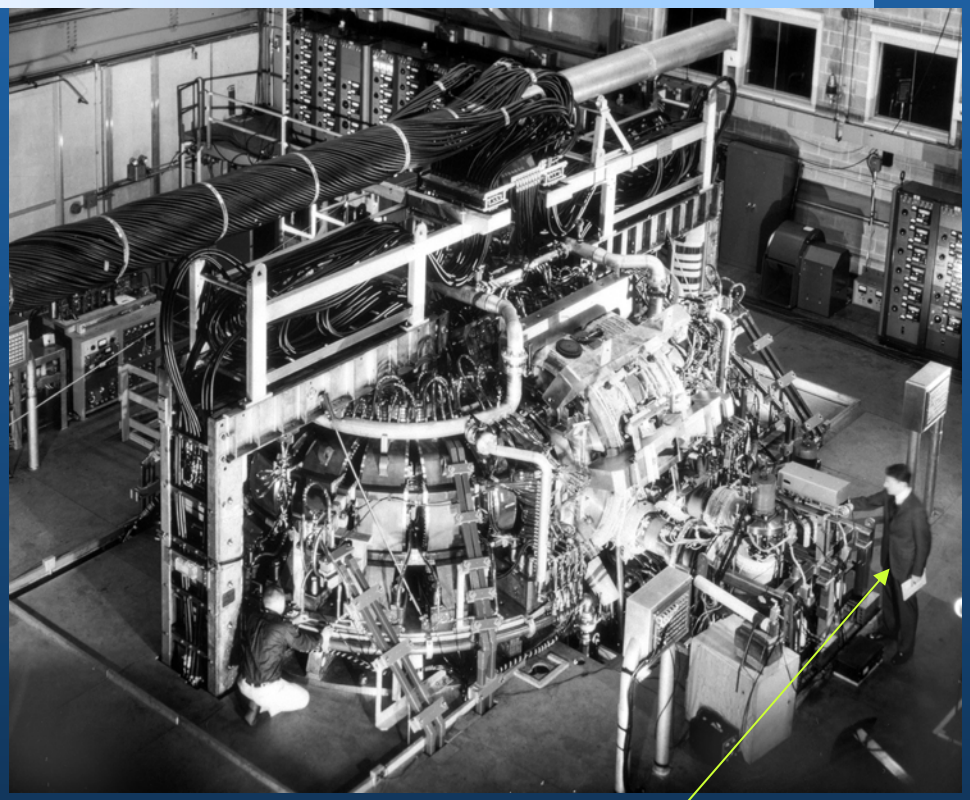
Stellarator Plasma

Stellarators are Not a New Idea!

An Early PPPL Stellarator Concept Shown at Atoms for Peace Conference, Geneva 1958

PPPL's First Major Experimental Device was the Model C Stellarator

- It operated in the 1960's.
- Early stellarators had a major shortcoming: they did not confine plasmas very well.
- Because of this, it was converted to a tokamak after the Russians announced its discovery and promising results.



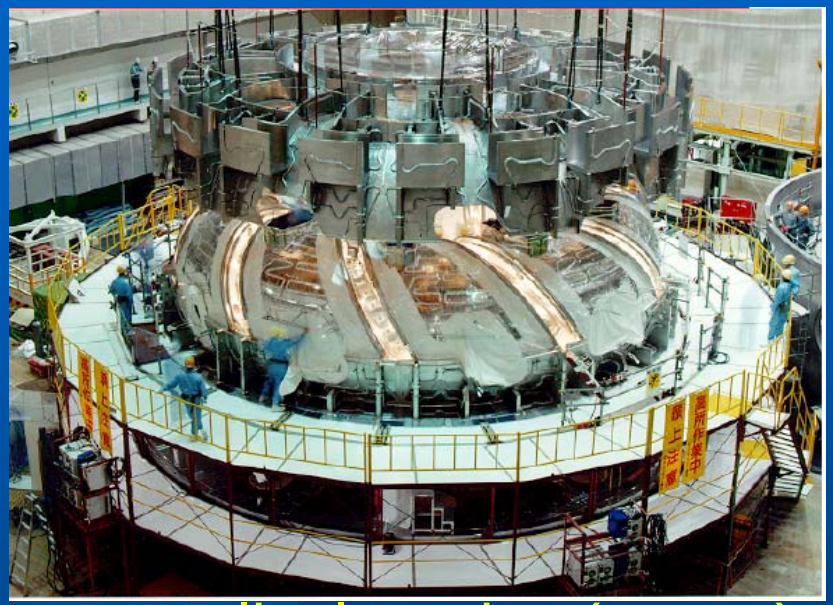
Dr. Lyman Spitzer

The Stellarator Rises Again and Returns to PPPL!

NCSX

- **Even though the tokamak became the predominant fusion concept, worldwide interest in the stellarator continued, especially in Germany and Japan.**
- **Analysis of the experimental data for C-Stellarator and other stellarators led to the understanding that the lack of confinement is primarily due to field errors.**
- **In the intervening years, major advances were made in three areas:**
  - Theory
  - Computation
  - Experimental programs
- **These advances have led to renewed worldwide interest, and PPPL in partnership with the Oak Ridge National Laboratory is developing a new "Compact Stellarator" that will be located at PPPL almost in the same location as the Model C Stellarator!**

The World's Newest Large ($1B) Fusion Facilities are Stellarators!

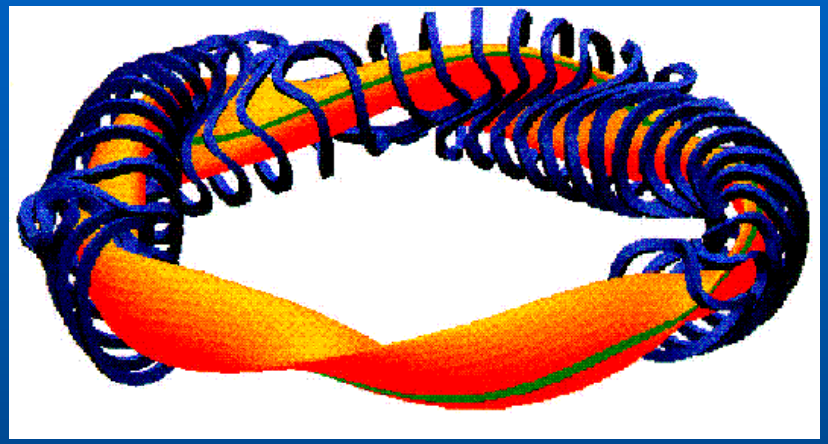


Large Helical Device (Japan)

S/C Magnets, B = 3→4 T

R=3.9 m, Aspect ratio 6.

operating since 1998.



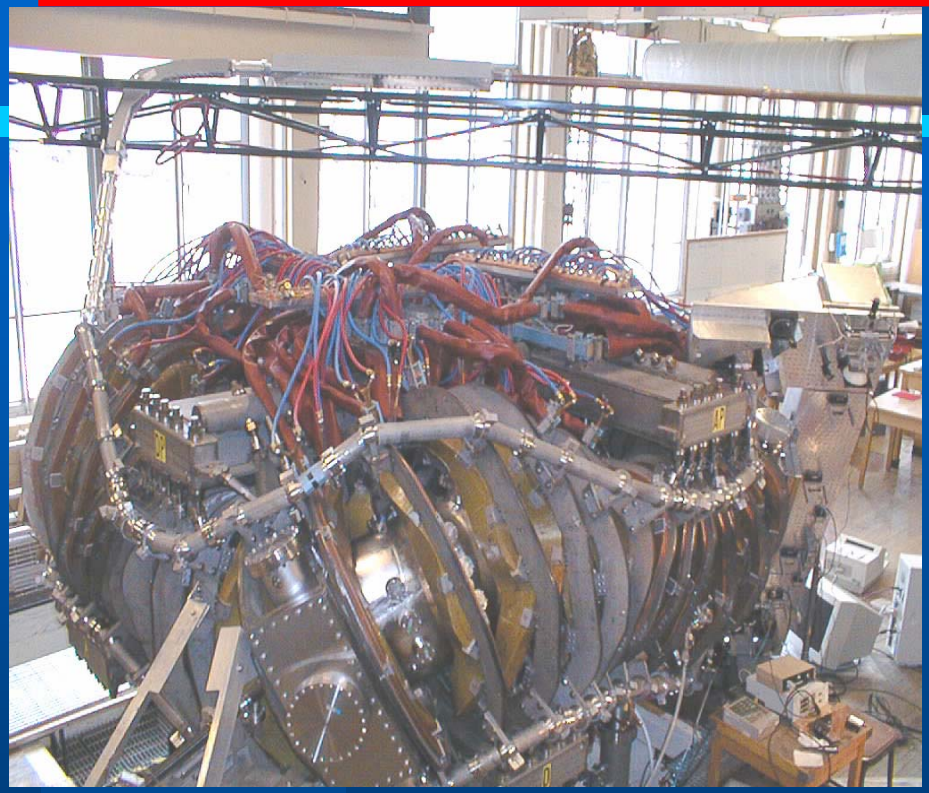
Wendelstein 7-X (Germany)

S/C Magnets, B = 3 T

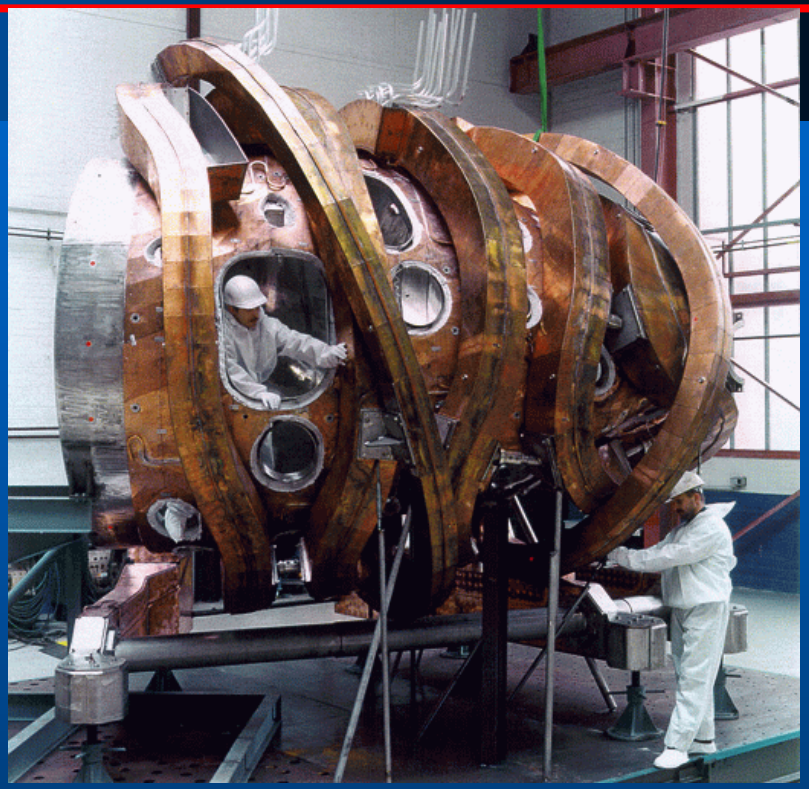
R=5.4 m, Aspect ratio 11.

under construction.

Stellarator Engineering and Fabrication Methods Have Kept Pace with Physics Advances and Needs



HSX (Univ. of Wisconsin) R=1.2 m
operating since 2000.

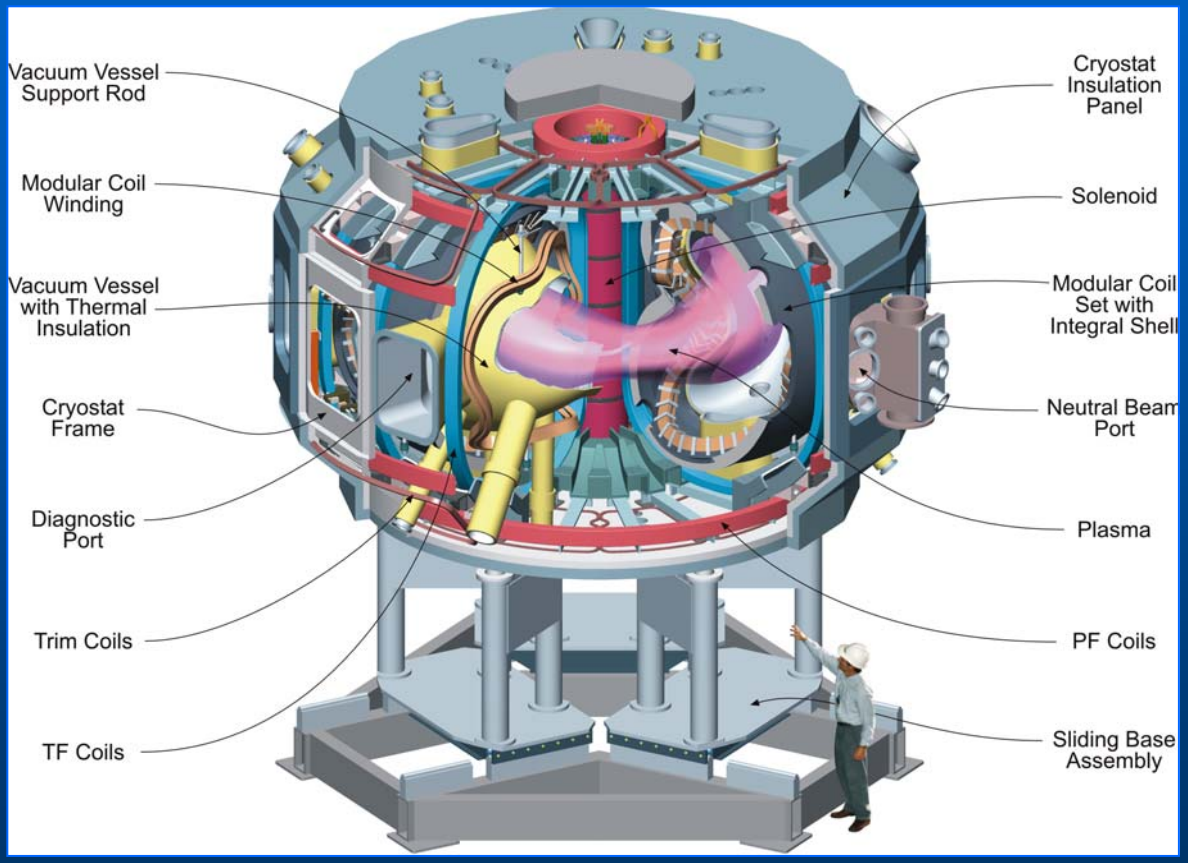


W7-X S/C coils (Germany)
under construction

- **Accurate 3D coils and structures have been built in a range of scales to support stellarator research.**
- **Substantial advances have been made in stellarator engineering methods.**

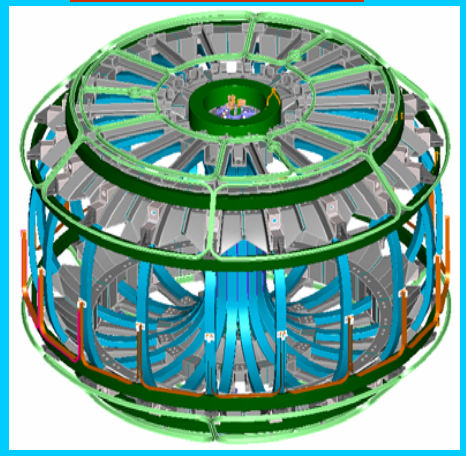
NCSX is the Central Element of the U.S. Stellarator Program

- First Plasma: June, ’08.
- Major radius, R = 1.4 m
- Magnetic Field Strength (B) =2.0 T (0.2 s pulse)
- All coils, including the Toroidal Field (TF), Poloidal Field (PF), Modular Coils, and Trim Coils are cryoresistive



Much NCSX is Conventional In Design and Construction, But There Are Two Key Components Which Are Clearly Unconventional.

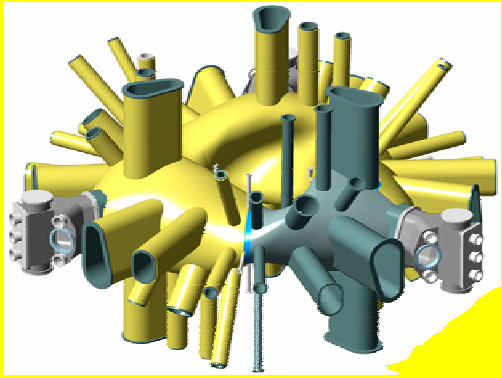
The Conventional Components



TF, PF, and Trim Coils

- Are conventional, cryo cooled copper coils.
  - Low stress; conservative designs.
- Structural supports consist of relatively straightforward stainless steel castings.

The Unconventional Components



NCSX Vacuum Vessel

NCSX Modular Coils

These were recognized as unusual and challenging from the manufacturing point of view from their conception.

The questions which often arise :

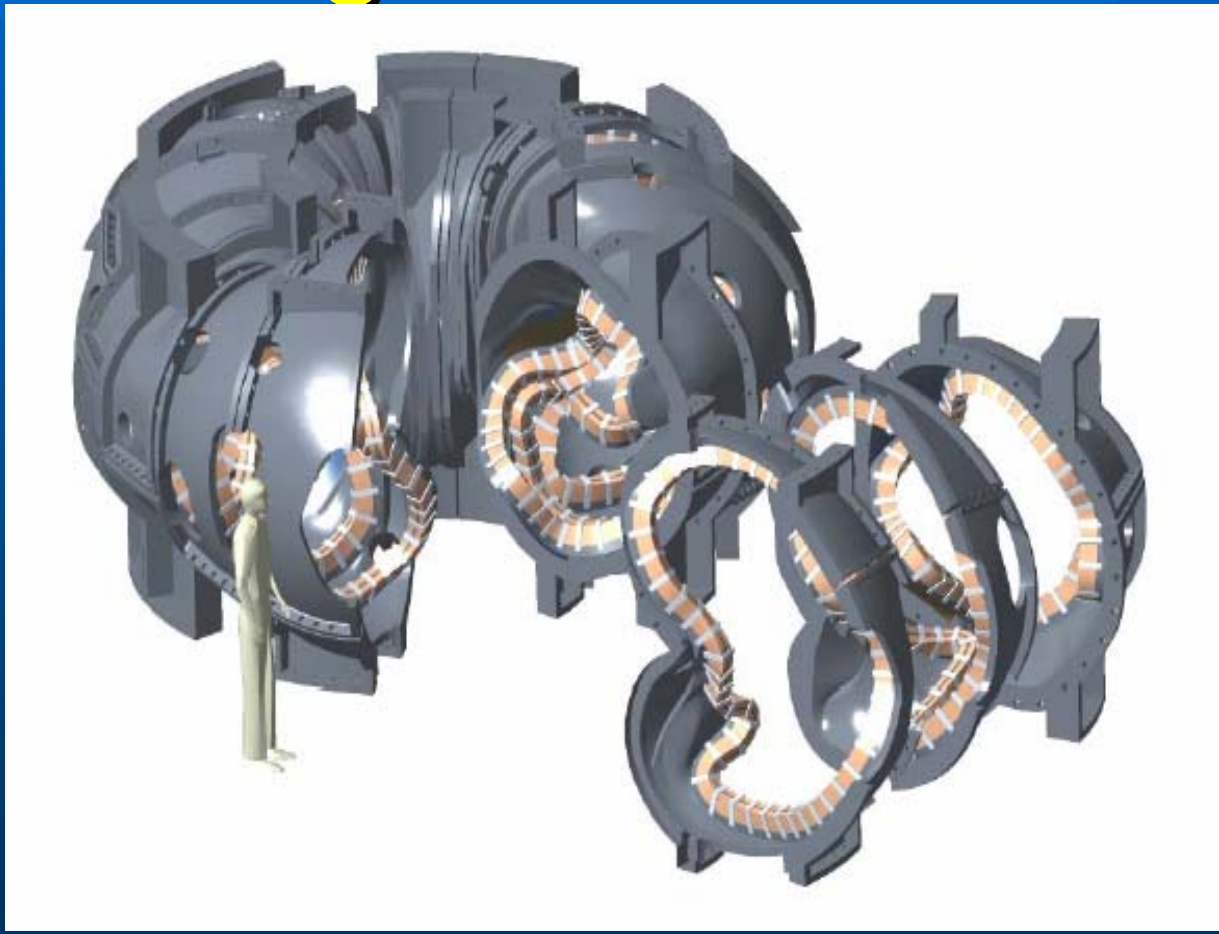
How can these parts be made?
Can these tolerances be achieved?
What will the costs and schedules be?

Unusual Key Component 1: The Highly Shaped NCSX Vacuum Vessel

- Provides a low impurity vacuum environment for the plasma.
  - Vacuum level 10^{-8} torr;
  - 150 ^{0} C operation, 350 ^{0}C bakeout.
- Made of Inconel 625, 3/8" thick.
- Fabricated in three field periods, welded together at assembly

Unusual Key Component 2: The Modular Coil Winding Forms

- Define the (3) precise coil shapes required.
- Withstand EM loads as high as 7000 lbs./ in.
- Deflect <0.020”.
- Machined stainless steel castings are the structural “backbone” of the machine:
  - Vacuum vessel, TF, and PF coils are all supported from it.



Prototypes Are Being Made of the Key Unusual Components

Two industrial teams in each area.

For a full-scale prototype 20 degree Vacuum Vessel sector:

- **Major Tool and Machine, Inc.; Indianapolis, In.**
- **Rohwedder, Inc., Orlando, Fla.;**
  - **And team member Precision Metal Works.**

***For a full-scale prototype winding forms*:**

- **Energy Industries of Ohio (EIO); Independence, Oh.**
  - **And team members Atlantic Technical Components; buyCastings, Inc.; MetalTek International; Magna Machine Co.; CA Lawton Co.; Deformation Control Technology Inc.; Finite Solutions Inc.; Altair Engineering Inc.; ARACOR**
- **J.P. Pattern, Inc., Butler, Wis.**
  - **And team members TKS Technical Innovation, LLC; Waukesha Foundry, Inc.; Remmelle Engineering, Inc.**

..And They Have Successfully Developed Them!

The first prototypes:

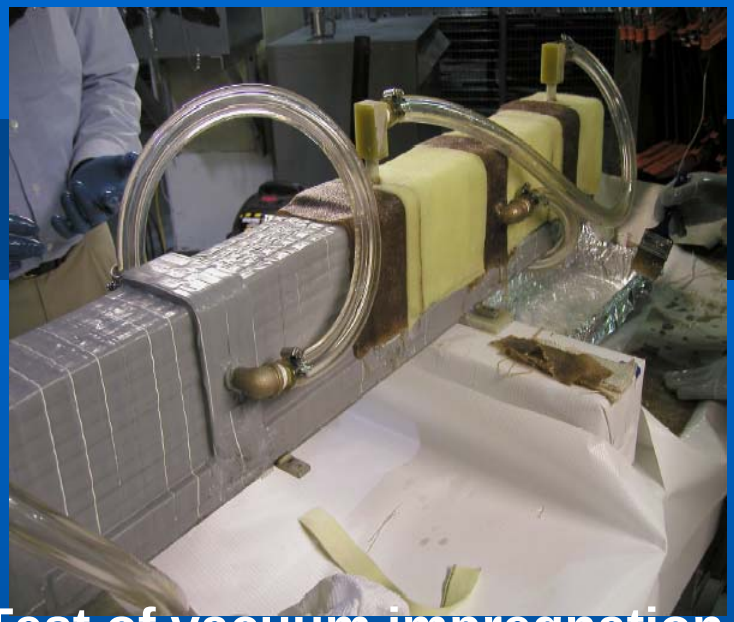
VV Prototype Sector

(Major Tool & Machine Inc.)

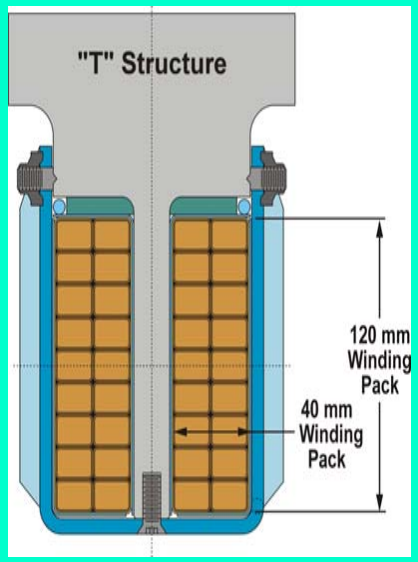
Winding Form Prototype

(EIO Team)

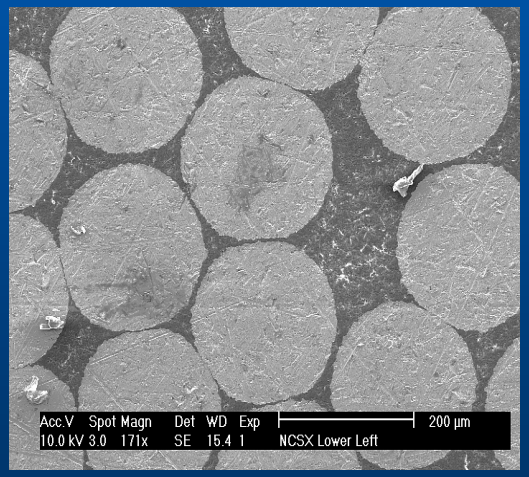
In Parallel, NCSX Engineering Is Developing the Winding Details



Test of vacuum impregnation



NCSX Winding Cross Section

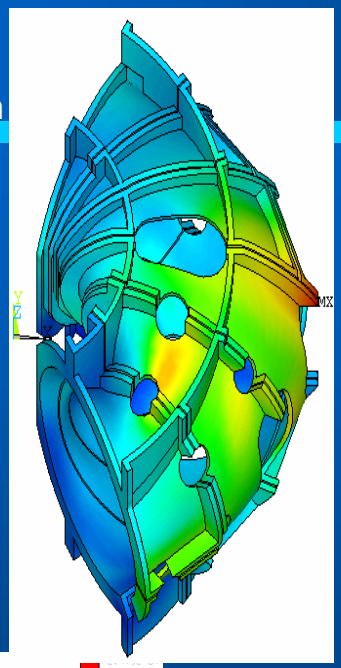


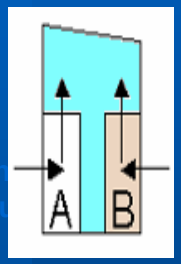
SEM photos of stranded cable conductor shows good epoxy penetration

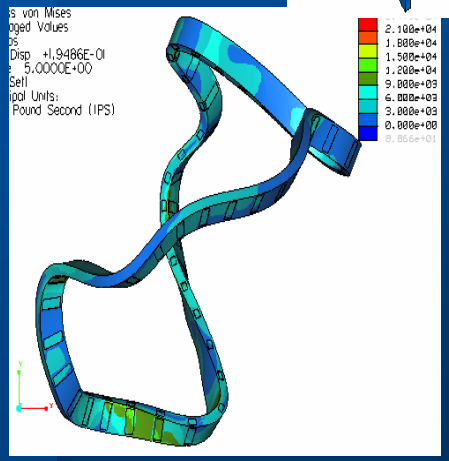
Intensive FEA Analyses Guide the Designs

NCSX

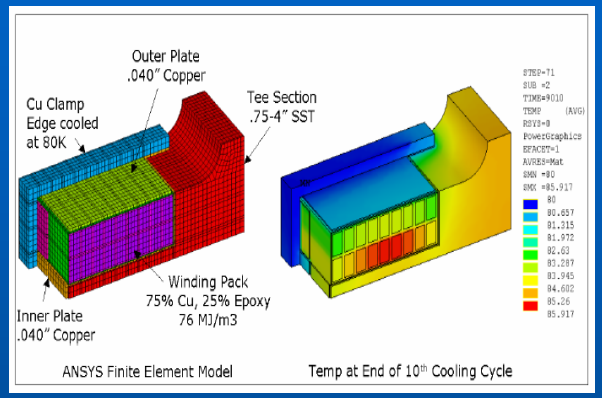
Shell has maximum deflection ~ 1 mm (for max loads)

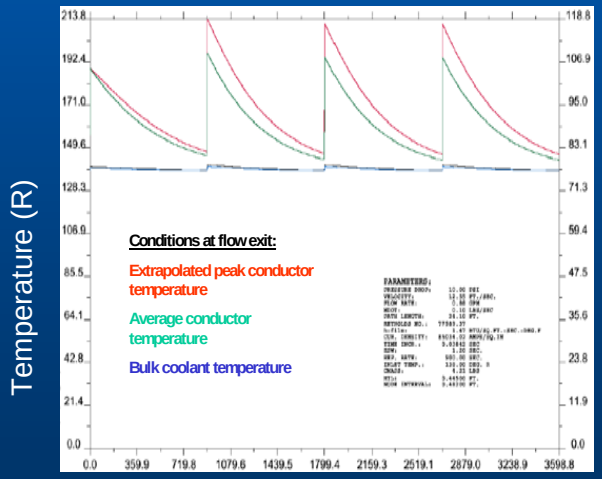






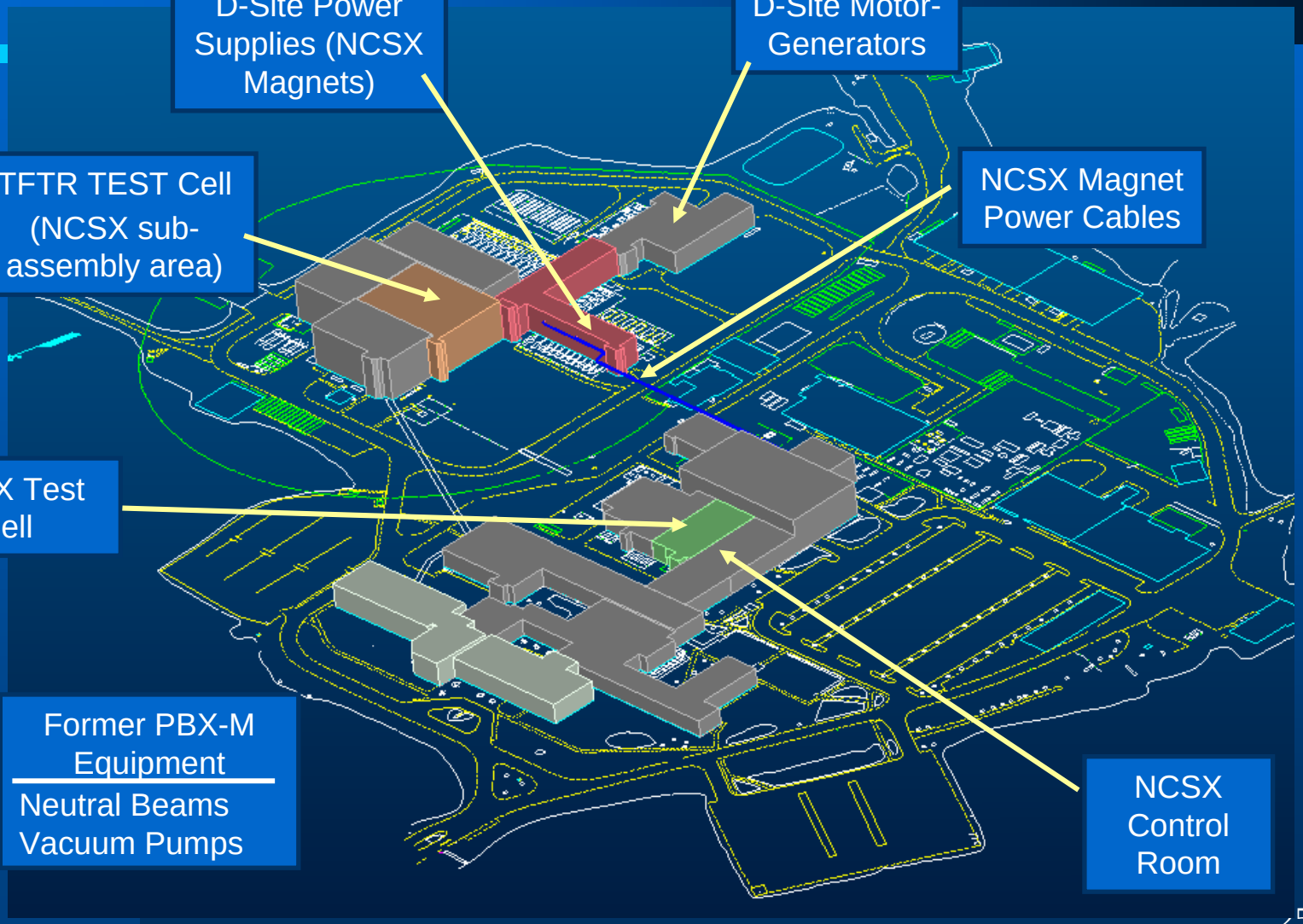
Mod. Coil Structural Analysis





Mod. Coil Thermal Analysis

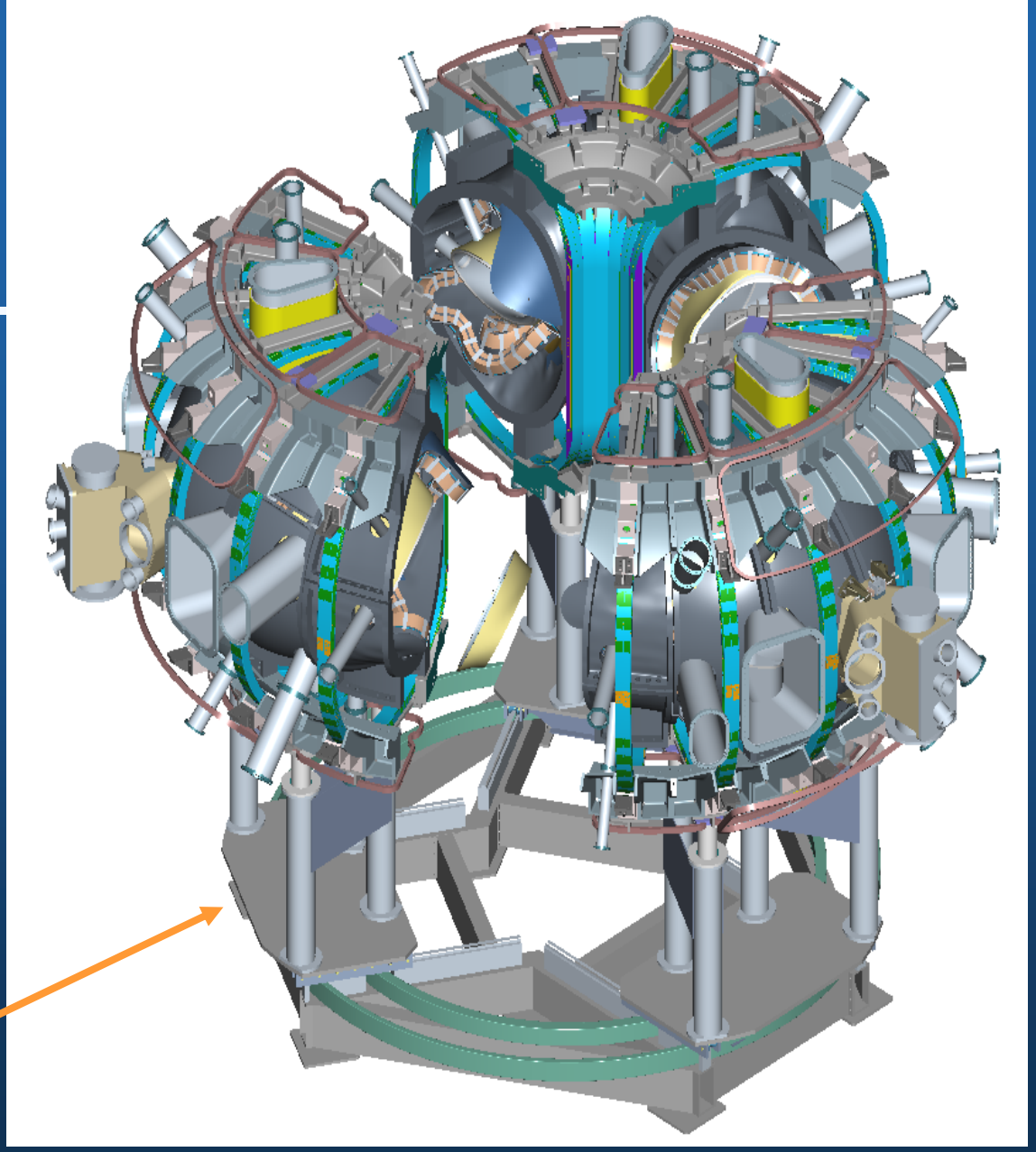
NCSX Uses Many PPPL Site Assets



Putting It All Together

NCSX

- NCSX is assembled from three identical assemblies.
- First plasma will be in June, ’08.



Click on figure for animation

Summary

- Fusion has great potential as a practically limitless source of clean energy.
- It still has a long development path; one if its most difficult problems: steady state operation. This is where the stellarator fits in!
- Stellarators may provide a solution to the problem of how to operate in steady state.
  - Through 3D plasmas and external controls.
  - More complex geometry, but well within the state of the art!
  - NCSX is the central element of the US Stellarator Program.
- We look forward to the construction of NCSX and to its first plasma in June, ’08!