Princeton University

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November 5, 2007

Dr. Jerry Faul
Princeton DOE Site Office
Princeton Plasma Physics Laboratory
Forrestal Campus

Dear Jerry,

I am pleased to transmit the final report of the NCSX Technical Construction Feasibility Review, held at PPPL last Wednesday and Thursday, and trust you will find it responsive to your charge.

I have conveyed my thanks to the committee members for putting in an extraordinary effort to produce a thorough, useful report on a very tight schedule.

Please let me know when it would be appropriate to release the report to PPPL Management. If there is any way I can be of further assistance just get in touch.

Sincerely yours,

Stew Smith

A. J. Stewart Smith, Dean
Class of 1909 Professor of Physics

cc: Ralph Brown, George Biallas, Peter Titus, Simon Anderson, Lutz Wegener, Frank Karl, Jeff Makiel, Christopher Eisgruber.

Department of Energy
Princeton Site Office
Review Committee

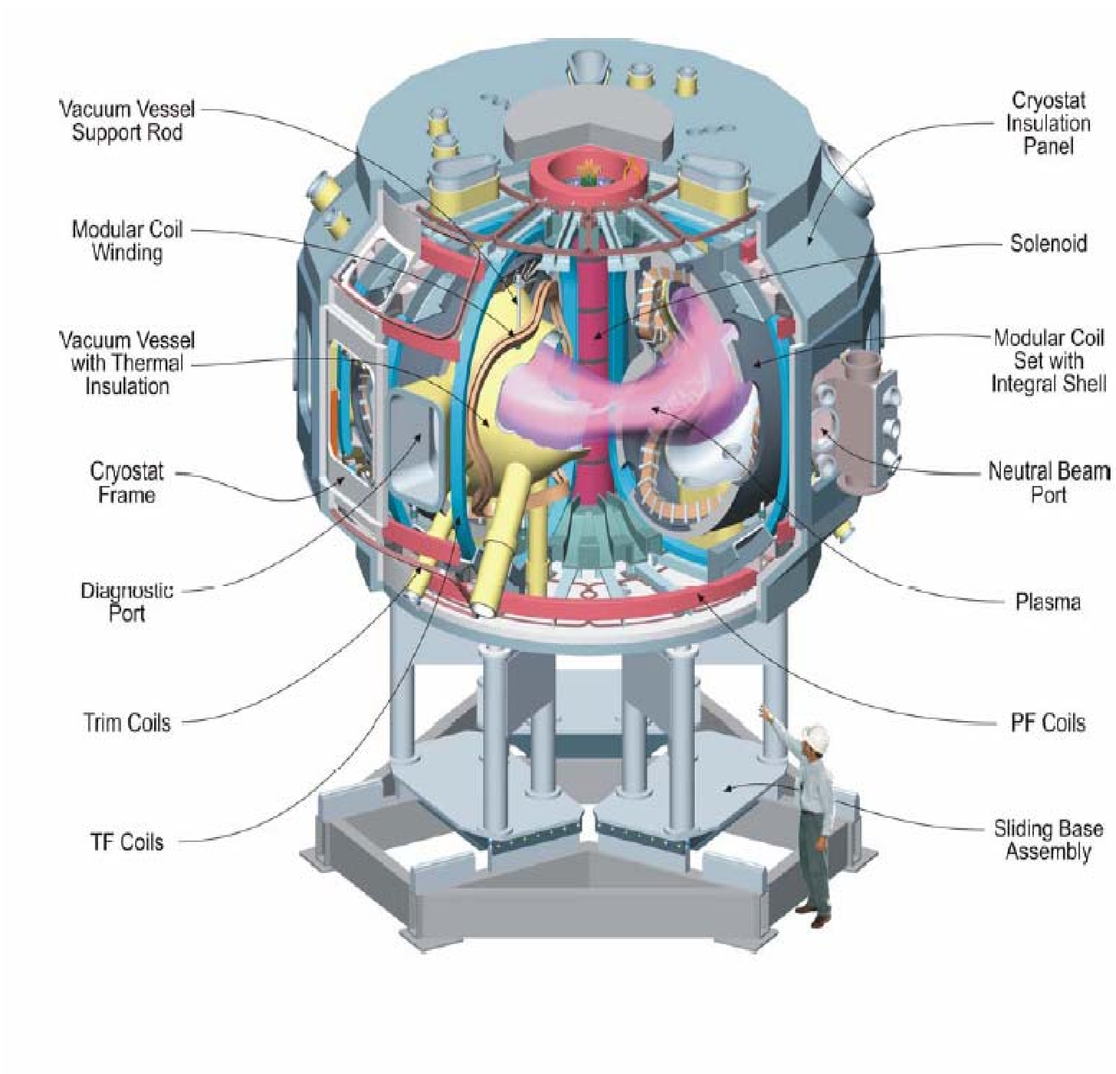
for the

Technical Construction Feasibility Review
Final Report

of the

National Compact Stellarator Experiment (NCSX) Project at Princeton Plasma Physics Laboratory (PPPL)

November 2007



NATIONAL COMPACT STELLARATOR EXPERIMENT (NCSX) PROJECT

Contents:

Executive Summary:

As requested by Professor A. J. Stewart Smith, the Dean for Research for Princeton University and Jerry Faul Manger of the Department of Energy Princeton Site Office a Technical Review of the National Compact Stellarator Experiment (NCSX) Project was performed at Princeton Plasma Physics Laboratory (PPPL) from October 31 through November 1, 2007. The purpose of the review was to evaluate the constructability of the stellarator to within the required tolerances based on the current state of the design. The committee was to focus on the stellarator core components and their assembly, and was not to include standard auxiliary equipment and support systems. The committee charge can be found in the appendices as a letter to Professor A. J. Stewart Smith from the DOE Princeton Site Office.

Previous reviews of the NCSX Project had not thoroughly investigated the technical design aspects for the assembly of the stellarator components and if these plans for construction could be accomplished within the required tolerances needed to meet operational performance. The NCSX Project Team presented to the review committee as documented talks the NCSX physics mission and global requirements, individual system requirements and design status, the need (and plan) for trim coils for field error compensation, detailed plans for Field Period Assembly and Final Stellarator Machine Assembly. The committee also toured the NCSX fabrication and development facilities for first hand observation of modular coil fabrication and Station-2 field period assembly.

Based on the information the NCSX Project Team presented, it is the opinion of each member of this committee that the NCSX Project Team can succeed in building and maintaining this stellarator. We base this opinion on the work and assembly plans presented.

Introduction:

The National Compact Stellarator Experiment (NCSX) is a fusion research project initiated in the Department of Energy (DOE) at Princeton Plasma Physics Laboratory (PPPL). The compact stellarator is one of several innovative magnetic fusion plasma configurations supported by the DOE Office of Fusion Energy Sciences (OFES). The NCSX device has the attractive potential of operating continuously and without plasma disruptions. Also, when extrapolated to a fusion power plant, the compact stellarator is projected to require low operating power compared with that produced by the power plant.

The mission of NCSX is to acquire the scientific and technological knowledge needed for understanding the behavior of compact-stellarator plasma confinement, evaluating the attractiveness of this fusion concept, and advancing the state-of-the-art, three-dimensional analysis of fusion plasmas. The NCSX project involves the design, fabrication, installation, and integrated system tests of a compact stellarator core device consisting of a highly shaped vacuum vessel, surrounding coil systems, enclosing cryostat and various auxiliary power, cooling, vacuum, cryogenic, and controls systems as well as a set of startup diagnostics. All of this equipment plus a control room will be located in existing buildings at PPPL that were previously used for other fusion experiments. The project is being led by PPPL with Oak Ridge National Laboratory (ORNL) providing major leadership and support as a partner.

Committee Findings:

As stated in the executive summary, it is the opinion of each member of the review committee that the NCSX Project Team can succeed in building and maintaining this stellarator. We base this opinion on the work and assembly plans presented. We feel that once the first Station 2 Modular Coil Half Period Assembly has been completed and shown to meet the required assembly tolerances then the major issues related to further assembly are similar and manageable with the techniques detailed and will therefore corroborate our opinion.

The NCSX Project Team presented the detailed core components, tools and fixtures along with the methodology and documented plans for the stellarator assembly. We found the Field Period Assembly from Station-1 through Station-5 to be well thought out with many hold points for metrology cross checks to ensure proper assembly within required tolerances. Final machine assembly, although mostly conceptual, is based on earlier field period assembly techniques and will include specific metrology steps to insure that tolerance goals are met. The challenging precision requirements for overall assembly are such that we believe the addition of the full complement of trim coils is vital for success.

The committee observed a deep understanding and broad development capability from the Project Team. They have the wherewithal and experience in stellarator physics, component/systems design and engineering, manufacturing capabilities of unique close tolerance core components, the analytical skills and design software tools required for this complex project. We found they had an excellent understanding of the technical issues and a demonstrated talent to formulate solutions as recognized in the need for “back office” support of fabrication and assembly. The project has in place state-of-the-art laser-tracker and coordinate-measurement-machine metrology systems that have been incorporated into all component fabrication and stellarator assembly plans. They have demonstrated an impressive ability to fabricate and deliver close tolerance core components such as the modular coil assemblies. We have found that all stake holders in the NCSX Project Team have formed a cohesive unit that is committed to the successful design, assembly, and operation of this stellarator.

Recommendations:

The committee in its deliberations had raised a number of issues and concerns that were passed on to the project team as homework for further discussion. The project initial responses to these can be found in the appendices of this report. The committee encourages the project to follow through on final resolution of these concerns consistent with the project's usual "CHIT" resolution procedure. All committee concerns and recommendations are detailed in the following:

1. With the loss of Wayne Reiersen, Brad Nelson, and potentially, Kevin Freudenberg to ITER, the committee is concerned that the resources will not be available to follow through on engineering tasks needed to support final design and assembly. The committee recommends that project management review and acquire adequate effort from these key individuals in support of component assembly through first field period assembly, Station-5. In addition, the experience at Wendelstein and at NCSX is that a significant engineering effort in the "back office" is needed to support metrology and assembly of a stellarator. The multitude of precision devices for final assembly should be qualified and tested in parallel to minimize exhaustive iterations. We recommend that project management insure adequate engineering staffing of this unique resource is planned for in the project scope and available at PPPL.

2. The committee supports the effort to find a dedicated project integration officer.

3. The work that Art Brooks does to adjust final positions based on measured coil positions is critical to the success of the final assembly accuracy. The committee has great respect for Mr. Brooks' capabilities, but given the consequences of an error in these calculations, Mr. Brooks' calculations should be carefully reviewed and cross checked.

4. The committee suggested that the coil deformations under electromagnetic and dead weight loading be included in the

calculations of the final modular coil positions, and needed shim dimensions. The present dimensional adjustments are effectively for zero field. It was suggested that an average operational loading be used for this calculation.

5. The issue of disruptions was answered for vessel response, and was quickly estimated at the review, for the modular coil forms. The estimate is that the effect is low, but these calculations should be finalized and documented.

6. The anisotropic elastic properties of the casting need to be quantified and factored into the analyses of the modular coil forms. Requirements for two directional testing were part of the original casting contracts, but were relaxed. It is believed that this was for reasonable cause, but given the potential effect on the elastic motions under load, a better understanding of this issue is needed. The project should review literature and correspondence and should inventory the available test samples from the NCSX castings. Tests on actual cast shell samples would be best. The available spare casting is a candidate for metallurgical evaluation. This spare casting has not gone through a heat treatment used on the production castings. The possibility of heat treating a sample taken from the spare casting should be investigated.

7. While correction coils are being designed, the possibility of future additions of correction coils outside the cryostat should be evaluated. These will require more amp-turns, but can be "low tech" and can be easily added at a later date.

8. Have load cells on support posts – especially where the support is redundant. i.e. multiple posts instead of three.

9. In station 6, the final machine assembly, vertical support is transferred from the assembly carts to six stainless steel support posts. This load transfer may introduce new displacements that need to be qualified by an additional metrology step, and adds a small risk of difficulties at a time when the full investment in the stellarator assembly has been made.

10. The committee recommends finite element analysis (FEA) analytic support at each step of the assembly process. The analytic models

should be benchmarked at the vertical to horizontal repositioning step for each of the modular coil forms.

11. The committee expressed concern that the modular castings vary in thickness and weight, and this may affect the structural response. The project responded with an explanation that the electromagnetic deformations were predominantly caused by the flexibility of the machined parts, but the effect of non-uniform shell thickness should be addressed in the FEA benchmarks.

12. A long term test of the preload retention of the bolting should be made at the actual design configuration used; thermal cycling should be included. In-service, operational monitoring of preloads of highly loaded bolts is strongly recommended. It was noted that initial torque tests on modular coil flange connection bolts was only 50% for those studs located in threaded blind holes; this was done to prevent deformation of the base material threads. We recommend that a test on a spare modular coil with 100% of the required torque be applied to these blind hole studs to understand the impact of having to possibly disassemble a completed flange connection.

13. The difficulty in accessing some of the modular coil form bolts has been mocked-up. The mock-up will be useful during assembly and operation. It would be wise to retain these for future use in servicing.

14. In-service, operational laser tracking of ample fiducials on the modular coil during operation is highly recommended.

15. Measurements of the alumina-to-steel friction coefficients should be made with more statistical rigor. The data scatter of the values presented raises the concern that the 2/3 allowable may not be sufficient to cover the uncertainties in assembled behavior. For design and construction the measured minimum values should be used to sufficiently account for uncertainties during shim production and assembly of modular coil flange connections.

16. The use for aluminum for TF and PF structural supports should be considered only after the effects of thermal differential contraction are analyzed. Aluminum components inside the cryostat have had to be removed from C-Mod. Difficulties with the use of aluminum and

stainless steel for Wendelstein's bus bar supports also support this recommendation.

17. The committee suggests that power lead routing, coolant line routing, etc. be determined as soon as possible to avoid downstream interferences.

Appendix A

Charge Letter to the Committee

Department of Energy
Princeton Site Office
P.O. Box 102
Princeton, New Jersey 08542-0102

OCT 2 – 2007

Dr. A. J. Stewart Smith
Dean for Research
Princeton University, Main Campus
4 New South Building
Princeton, NJ 08544

Dear Dr. Smith:

SUBJECT: TECHNICAL REVIEW OF THE NATIONAL COMPACT STELLARATOR (NCSX) PROJECT AT PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

As we have discussed, the DOE Office of Science must make a decision regarding the future of the NCSX Project in November 2007. In order to be fully informed regarding the viability of completing construction and successfully operating this device, we are requesting that a comprehensive technical design/constructability review of the project be performed by the University. The purpose of the review is to determine whether there is a high level of confidence, based on the current state of design, that NCSX can be built and maintained within its required tolerances.

It is understood that this design review can only address the design activities completed to date. Future design activities will require additional reviews. It is expected that this review will focus on the stellarator core components and assembly, and will not include standard auxiliary and support systems. It is also expected that this review committee will consist substantially of technical experts that are external to the NCSX project team and the participating laboratories.

We request that the University conduct this comprehensive design review and submit a final review report to me by November 5, 2007. Representatives of my office would also like to participate in the review as observers.

Appendix B

Review Committee and Participants

Review Committee:

Ralph Brown, Brookhaven National Laboratory (chair)
Simon Anderson, Univ. of Wisconsin
George Biallas, Thomas Jefferson National Accelerator Laboratory
Frank Karl, Brookhaven National Laboratory
Peter Titus, MIT
Lutz Wegener, IPP-Greifswald

DOE Observers:

Jeff Makiel, DOE-Princeton Site Office
Barry Sullivan, DOE, Office of Fusion Energy Sciences

NCSX Team:

J.L. Anderson, PPPL
A. Brooks, PPPL
M. Cole, ORNL
L. Dudek, PPPL
R. Ellis, PPPL
R. Goldston, PPPL
R. Hawryluk, PPPL
P. Heitzenroeder, PPPL
J. Lyon, ORNL
H. Neilson, PPPL
E. Perry, PPPL
S. Raftopoulos, PPPL
S. Smith, Princeton University
M. Viola, PPPL
M. Zarnstorff, PPPL

Appendix C

Review Agenda

AGENDA

Wednesday, October 31, 2007, LSB 318

8:00 a.m.	**Executive Session** / *Continental Breakfast*
8:30 a.m.	**Princeton University Welcome** R. Goldston (PDF)
8:35 a.m.	**NCSX Introduction** J.L. Anderson PPT PDF
8:45 a.m.	**NCSX Physics Mission and Key Requirements** H. Neilson PPT PDF
9:15 a.m.	**NCSX System Requirements and Design Status** P. Heitzenroeder PPT PDF
10:30 a.m.	**COFFEE BREAK**
11:00 a.m.	**Tour of NCSX Manufacturing Facility**
12:00 p.m.	**Lunch**
12:30 p.m.	**Field Period Assembly Plans** M. Viola PPT PDF
1:10 p.m.	**Final Machine Assembly Plans** E. Perry PPT PDF
1:40 p.m.	**Trim Coils for Field Error Compensation** A. Brooks PPT PDF
2:10 p.m.	**Summary** J.L. Anderson PPT
2:15 p.m.	**COFFEE BREAK**
2:30 p.m.	**Committee Executive Session**
4:30 p.m.	**Committee Questions for NCSX Team**
6:00 p.m.	**Adjourn**

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Thursday, November 1, 2007, LSB 318

8:00 a.m.	**Executive Session** / *Continental Breakfast*
8:30 a.m.	**Committee Questions for NCSX Team**
9:30 a.m.	**Committee Executive Session**
12:00 p.m.	**Lunch**
12:45 p.m.	**Closeout Briefing**
1:30 p.m.	**Adjourn**

Appendix D

Response Summary

No.	Comment	NCSX Plan
1	Suggest independent check of codes used by A. Brooks to guide coil shifts	Stuart Hudson plans to do this. Schedule needs to be established.
2	Suggest cross-checking of A. Brooks' dimensional guidance calculations.	This is required by PPPL Engineering Procedures and will be instituted.
3	Committee requests weight information for the NCSX modular coil winding forms. Possible concern: the wall thicknesses may vary sufficiently enough to cause non-stellarator symmetric variations in deflections.	Weight information is in the documentation packages for the MCWFs. This information will be gathered and supplied. However, since the max. deflections are due to primarily to deformations of the T sections which are machined to a uniform thickness, we do not feel that this is an issue. Refer to Fig. 1.
4	An ITER R&D report on 316 castings indicates that the modulus of elasticity is very anisotropic.	NCSX is reviewing this report. There are some obvious differences in the material - the ITER casting used chromate sand for rapid cooling, which may have resulted in non-uniform cooling rate and the chemistry is close but not exactly the same. NCSX is investigating if a modulus sensitivity FEA analysis can be readily performed and if we might be able to determine anisotropic characteristics by compression testing of a cube of material.
5	FEA model analysis of the NCSX assemblies in the various stages as they progress through assembly suggested to provide insight to structural deformations and possible changes in plans.	This is planned, and some has already been done (ex: single MCWFs and "3-packs"). Analyses of the torus assembly with various support conditions are also planned.

6	Long term stability of bolted connections should be studied.	This is planned. Included is thermal cycling and long-term bolt tension stability. See Fig. 2.
7	Fiducials move as the bolts between MCWFs are tightened.	Some studies were made during assembly trials; it was found that movement occurs during tightening to 50% torque, with minimal motion after that. We plan to study this more as the actual assembly work gets underway. Fiducials on the shell (vs. the flanges) are used, since flanges are more likely to move as the bolts are tightened.
8	The friction allowable should be based on the lower bound of the friction test data.	Agree – the figure showing the data vs. requirements in this manner is attached as Fig. 3.
9	Disruption loads were not included in the modular coil analyses – how much of an impact does disruptions have on loads?	A simplified SPARK model was run to estimate the added shear forces across the MCWF joint from a plasma disruption. A 350 KA center plasma instantaneous disruption was considered (ie inductive solution) without the shielding effects of the VV. The maximum eddy currents are ~50 KA. The fields were assumed to be ~0.5 T based on trim coil calculations. If the currents are on either side of the flange and in opposite directions, a shear force of 25 KN/m (143 lb/in) or ~ 570 lb per bolt. This compares to the design load of 15,000 lb shear per bolt.
10	Suggest that power lead routing, coolant line routing, etc. be determined as soon as possible to avoid downstream interferences.	Agree – these activities are currently underway; ORNL and PPPL keep in close contact on these routing activities. A typical integrated model is shown in Fig. 4.

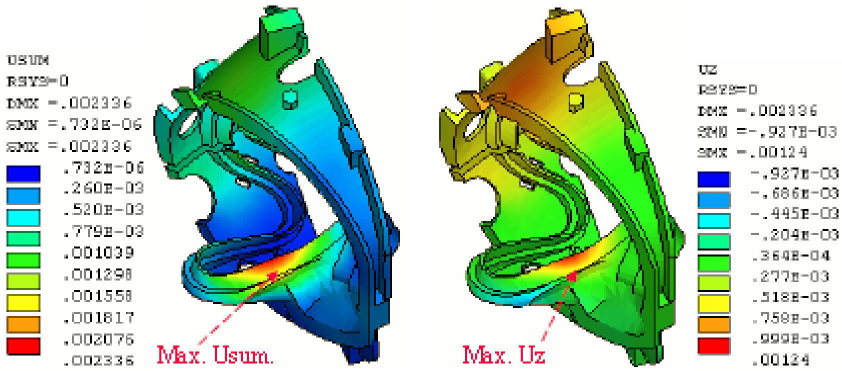

Fig. 4.2.1-1: Maximum displacements occur at wing of shell Type B

Fig. 1. Details of maximum displacement location. This is from an earlier model, and therefore the precise displacements are not comparable to the updated analysis run presented, but are illustrative of the localized displacement behavior. Most of the displacement is due to displacements in the septum of the T section rather than the wing itself.

Fig. 2. Summary of currently planned bolt tests

Outboard Interface-Bolted Joint Tests-Tension		
1421-3067		Procure 2 studs f/joint test. Use existing part
1421-3075		Setup test fixture &perform JHA &pre-job brief
1421-3077		Meas joint deflect vs preload &loss of preload
1421-3079		Measure joint deflec & preload v. temp @80K
1421-3084		Measure joint deflection &preload v. cool down cyc
1421-3087		Perform pullout tests for tapped holes
1421-3081		Meas joint deflect & preload v. time (days) at
1421-3090		Document &conduct review of test results
Outboard Interface-Bolted Joint Tests-Shear		
1421-3112B		Procure/fab parts for test &initial assembly
1421-3115B		Assemble &test
1421-3119B		Document test results

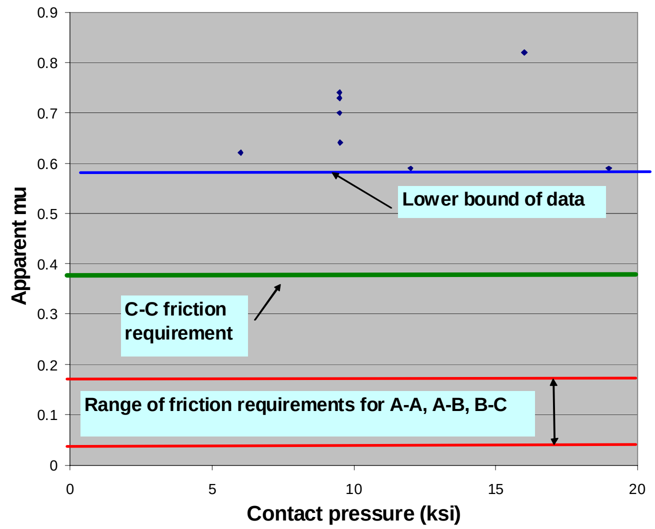

Fig. 3. Friction requirements vs. data

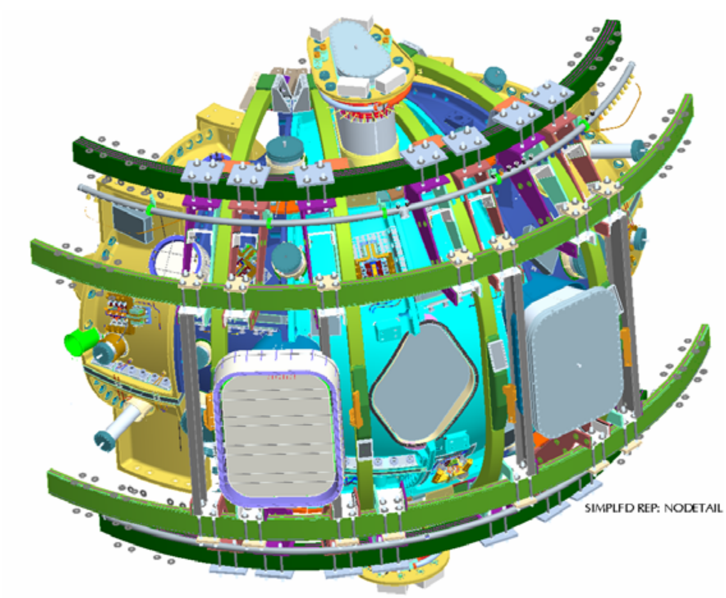

Fig. 4. Full Period with PF coil shown as segments. Note lead details – routing of coolant lines, bus connections, etc. are underway and will be added as details are developed.