NSTX-U IN-VESSEL CONTROL COILS DESIGN CONCEPT

Neway D. Atnafu, A. Brooks, D. Cai, J. Dellas, S. Gerhardt, J. Menard, M. Ono, G. Labik, P. Titus
Jorge R. González-Teodoro

[1]*Princeton Plasma Physics Lab, Princeton, NJ, USA*

Abstract— **a successful conceptual design was completed to develop in-vessel control coils (Non-Axisymmetric Control Coils or NCC). The NCC coils are a series of saddle coils that are intended to satisfy a number of physics criterion including magnetic breaking, error field control, fast Resistive Wall Mode (RWM) control and ELM stabilization. Customized Mineral Insulated Cable (MIC) was selected for the conductor material. The MIC was made from oxygen-free copper conductor, high purity Magnesium Oxide powder insulation and 304 stainless steel sleeve cover. Sample MIC was purchased from an outside supplier and various tests were conducted for design and performance verification including high voltage testing, which necessitated the development of special test terminations. A concept design was also developed for terminating the MIC ends using non-conductive and vacuum sealed technique. Two alternative designs were proposed for joints inside the vacuum vessel. The NCC Coils are designed to be mounted in-front of the primary passive plates and underneath the Plasma Facing Components (PFC) tiles. The passive plates will be modified to accommodate the coils. A new PFC tiles design concept was developed using High-Z materials. New designs for the penetrations through the vacuum vessel (VV) wall were developed. One port per coil was planned. A new power patch panel will be required to provide the ability for various combinations of connections between the NCC, the existing RWM Coils and the existing Switching Power Amplifier (SPA) power suppliers**.

***Index Terms*— Fusion Diagnostics, In Vessel Coils, Control coils, MIC**

I. INTRODUCTION

PPPL is an US Department of Energy National Research Laboratory managed by the Princeton University. PPPL is world renowned research center for nuclear fusion and plasma technology. NSTX-U (National Spherical Torus experiment – Upgrade) is PPPL's flagship fusion experiment. The Non-axisymmetric control coils are a series of saddle coils that are intended to satisfy a number of physics criterions including magnetic breaking, error field control, fast Resistive Wall Mode (RWM) control and Edged Localized Mode (ELM) stabilization. The operation mode design specification is 3KA, 60 Hz, 1 KV circuit voltage, 5 seconds pulse in 20 minutes interval for 8 hours per day.

In order to achieve this criterion, 3 different configurations have been physics analyzed. The final design concept that was chosen was 12x2 arrangement (meaning 12 coils above and 12 in below midplane) over the 6x2 and 12x1 arrangement. Figure 1 shows the NSTX-U NCC coils arrangement.

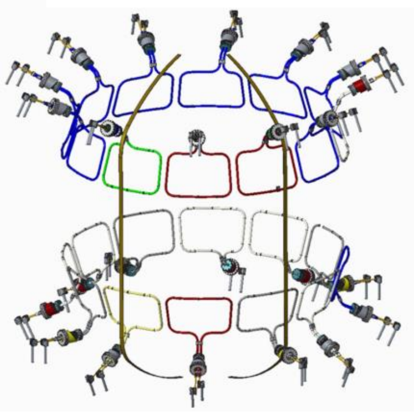

Fig. 1 In Vessel coils Distribution.

In order to develop this conceptual design, 24 new ports will need to be drilled through the vessel wall. Also the passive plates will have to be modified and new PFC tile designs will be needed as well. A total of 6 different types of coil design are needed. There are a maximum of 8 similar coils in the above midplane geometry and 5 similar coils in the below midplane geometry. Figure 2 shows the port penetrations of the vacuum vessel.

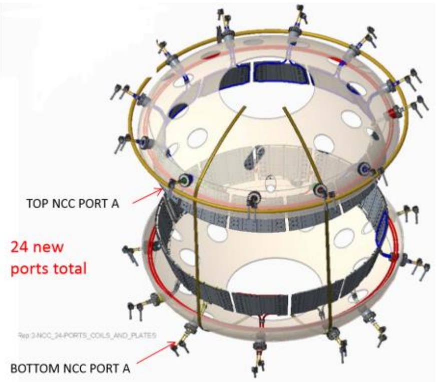

Fig. 2 In Vessel new Ports

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II. NCC DESIGN

The conductor selected for the conceptual design is MIC with copper conductor, ultra-high purity MgO insulation and stainless steel sheath. A hollow conductor with active water cooling capability was investigated, but it was determined by engineering analysis that a solid conductor was the better alternative for the given design parameters. The cable absorbs moisture and becomes conductive within minutes exposed to air. The MgO insulation properties can be recovered by baking it at 500 C (the duration is not developed yet). The moisture usually penetrates a few inches deep from the cable ends, thus torching the ends to 500 C is equally successful curing technique and more convenient. The MIC ends can be sealed to prevent exposure of the MgO to moisture using Hot Glue Stick, Stycast-2651 or H-77 UHV Sealant [NOTE: These sealants are only used in atmospheric conditions during fabrication].

Joints Design and testing

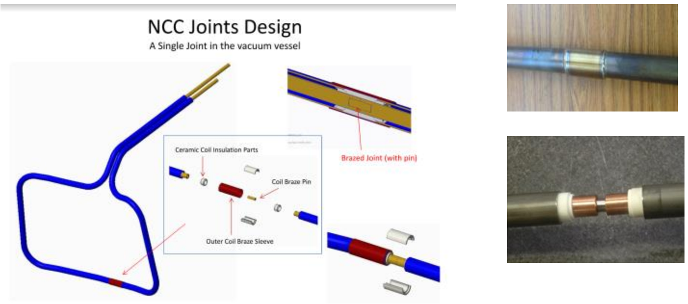


Fig. 3 NCC Joints Design

The design of the coil was difficult to be formed from a single cable. At the same time, it is desirable to minimize or eliminate the joints to reduce the risk of leaks. Thus, a joint design (brazed join with pin) was developed. The joint design detail is shown in Figure 3. A prototype of the joint was developed, tensile tested and passed 4 KV hi-pot test. The coil braze pin is inserted into holes drilled into the conductor. Ceramic parts surround the braze joint. A braze which was pre-positioned to the side of the joint, is slipped over the joint and is welded to the jacket to join to the MI cable.

Machining the MgO end preps was difficult and had some issues, other alternatives were planned to be investigated to solve this manufacturing issue in the next design step.

The counter-bore on the ceramic ends provided a longer electrical break-down path in the MgO. In this machining operation, testing showed that sometimes a good quality fabrication is achieved but sometimes the result was a crumbled insulation profile. Machining the MgO at the inner diameter shall be investigated further.

Bend radius tests for the MIC

Several bending tests were developed with different samples of varying bend radii. The deformations were evaluated to select the best bend radius to use during forming the coils. The samples were hi-pot tested to support the evaluation process. Further investigation is required. Figure 4 shows PPPL technicians performing tests on bend samples.

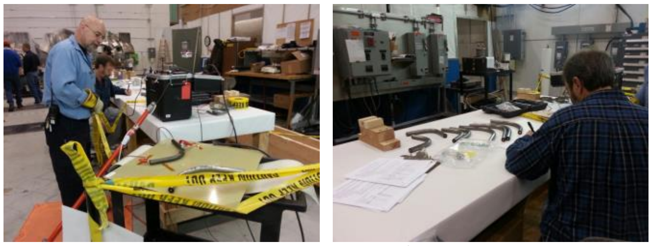


Fig. 4 PPPL Technicians Performing Tests

Clamps Design

There are 14 clamps per coil. The engineering analysis results are discussed under Section VII of this paper. Figure 5 shows an assembly model of the clamps, coil and a passive plate.

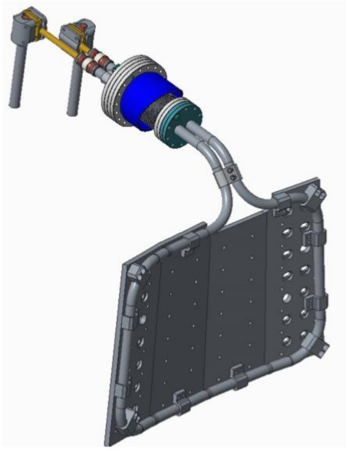


Fig. 5 In-Vessel Camp Distribution

III. NCC COIL FEEDTHROUGH DESIGN

A Feedthrough was designed with all conflat sealing, as shown in Figure 6. The design uses coil interconnection from the vacuum side, which is judged less desirable for maintenance. Bellows are incorporated into the design to allow relative motion of the passive plates and vessel during disruptions and during bake-out. Further investigation is needed.

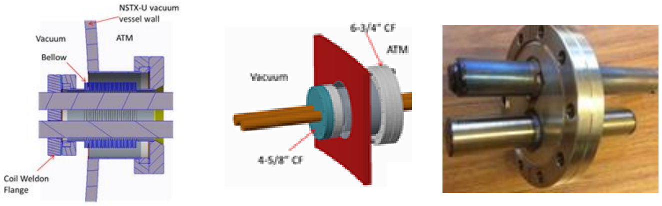


Fig. 6 In-Vessel Feedout Model and Prototype

Vacuum Testing and MgO Conductance

Two vacuum tests were conducted to find out the conductance of the MgO insulation layer, so as to understand the leakage behavior in case the MgO is exposed to vessel vacuum. The first test was conducted with 6” long sample, and the second test with a 5 ft long sample. For the first test both ends of the 6” long conductor were sealed. A ¼” vacuum pumping port was in the middle and a residual gas analyzer (RGA) was attached. The vacuum test obtained H_2, OH, H_2O, O_2 and CO_2 as main components with and without the MIC sample included. For the first test of the short sample, the base pressures reached 1.1E-07 Torr after 24 hours.

The second vacuum test was conducted using a 5 ft long coil sample. Figure 7 shows a photo of the test setup. The pump down curves for P1 which is located at far side of the coil and P2 which located at the vacuum pump side of coil are shown in Figure 8.

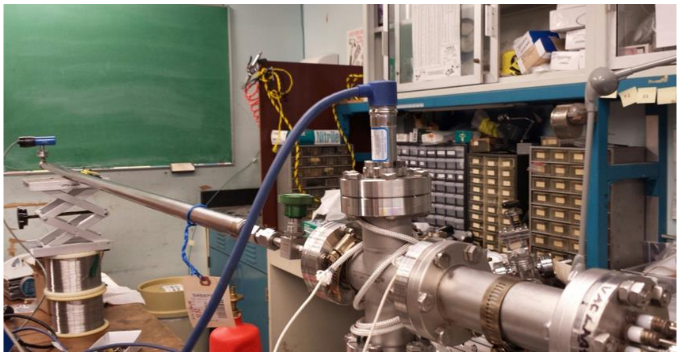


Fig. 7 Vacuum Pumping Test Setup

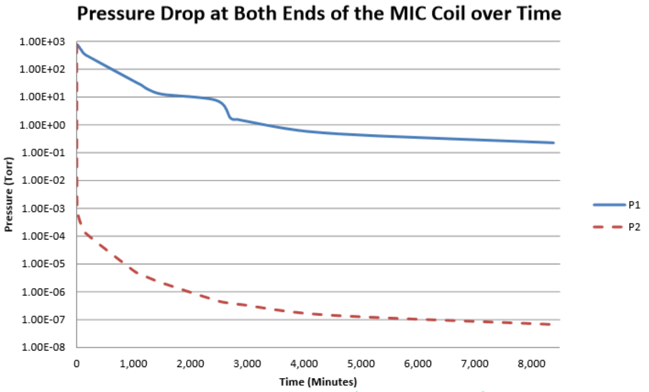


Fig. 8 Vacuum Pumping Test on the 5 ft Sample

For second test, the base pressure reached 6.7E-08 Torr after 6 days at the end nearest the vacuum pump, and sub-Torr in 6 days at the end farthest from the vacuum pump. It is concluded that the conductance of the MgO insulation layer is high enough so that the pumping down of the real control coil can be achieved in a reasonable amount of time.

Termination Design

A ceramic break termination design was developed in collaboration with an outside manufacturer. The break was rated for 5 KV and performance tested. A new revised design is being prepared for 10kV rating to satisfy a revised requirement of the machine. The brazed joint of the ceramic break can withstand the maximum operating temperature. Figure 9 shows cross-sections of the break.

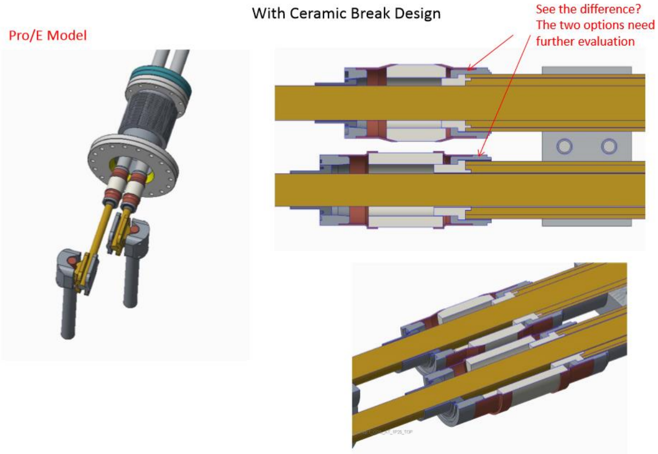


Fig. 9 Detail of termination Design options

IV. ELECTRICAL POWER INTERFACE DESIGN

The present configuration is composed of 2 SPA units, each with three individually controllable sub-units with dedicated cabling. This provides the capability to individually control each of the six existing RWM coils. Every SPA sub-unit is rated for 3,333 A for 6 seconds, every 300 seconds minimum. The SPA unit’s dc power supply is a Transrex converter using thyristors.

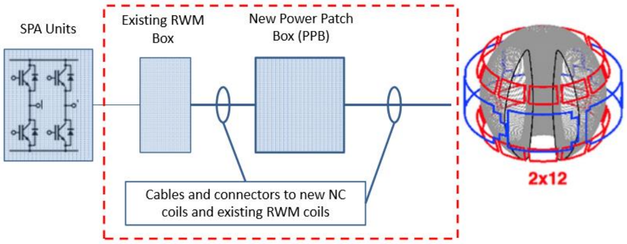


Fig. 10 Electrical Power Interface

For the new configuration, a new power patch box will be provided that allows for various coil interconnections to the SPA units, as required by the Physics operational scenarios. Also new cable-to-coil connections and cable routing is needed. Figure 10 shows a schematic diagram. Adequacy of the existing SPA units to support the new coil loading was confirmed via a PSCAD modeling analysis.

The new Power Patch design includes 11 possible configurations for the 24NC coils and 6RWM coils. It requires 60 cable connection points.

Cables terminate on copper bus segments; in addition, the interconnections for different coil feed scenarios could be made with short bus cross connections or cable jumpers.

Two options have been reviewed for the cables to the CC and RWM coils. The SPA units power circuits utilize IGBT (Insulated gate bipolar transistor) H-bridges, which generate fast rate of rise voltages at a switching frequency of 7.5 kHz, therefore shielded cable options were considered.

- Option 1

Commercially available variable frequency drive (VFD) cables are used as low voltage (2kV or less) power cables with shield for EMI minimization. These cables come with 3 conductors plus three symmetrical grounds for returning three phase unbalanced VFD stray currents. The customization required for the coil circuits would be a two conductor cable with a braided shield and two symmetrical grounds. (See Fig.11)

- Option 2

Flexible cable with 5kV voltage, shielded and single conductor mobile substation power cable (SH type). Two cables from each coil would be tied together during installation to reduce loop inductance (overall increase in loop inductance compared to option 1 due to addition spacing between conductor (5kV insulation plus shield and jacket)).

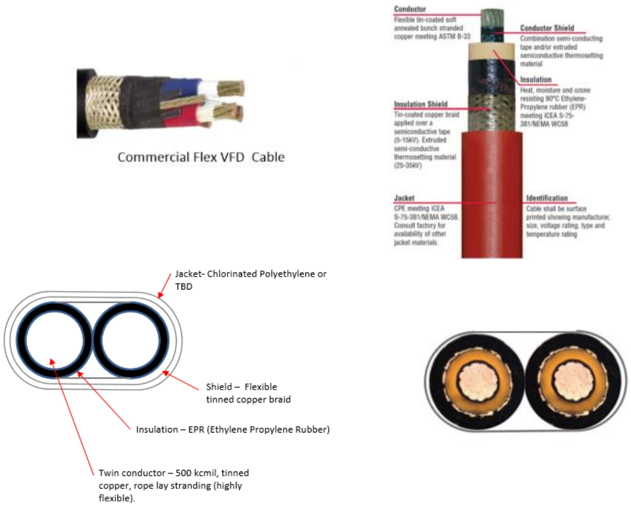


Fig. 11 Cabling Options

Several modifications to the current RWM Box is required:

1) *Removal of the existing RWM coil cables and install and terminate new cables and cable shields. Enlarge existing cable entrance holes to allow for cable glands for shielded cables to be installed.*
2) *Existing grounding cables to grounding switches to be reconnected across SPA sub-units feeds.*
3) *Reconfiguration of interconnections of SPA sub-units feeds.*

- MI cable testing of 10X Design Margin

Because the output voltage of the SPA units is 1kV, the MIC should be able to withstand 10kV hi-pot. (See Fig.12)

Two concerns about testing at the design margin level were:

-Past Hi-Pot testing on MI samples showed failure at the cable ends at around 6 to 7 kV.

-HV cable terminators for MI cable are not commercially available.

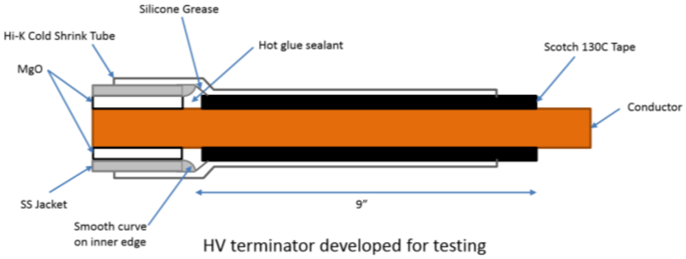


Fig. 12 HV terminator

The solution to the above concerns was to implement a unique application of commercially available Hi-K cold shrink cable terminators for MI cable. The cold shrink terminator prevented the cable ends from failing, such that the withstand voltage of the mineral insulation could be demonstrated. As a result of this, all test runs experienced breakdown at 10kV or higher (higher than calculated value of 7kV which was based upon manufacturers value of 3kV/mm).

At the breakdown voltage for each run, there was a clearly audible, static-like discharge sound. It is a possibility that test specimens did not contain any MgO block boundaries (used in forming the insulation) which are potential weak points. It is also possible that the manufacturer's value is conservative.

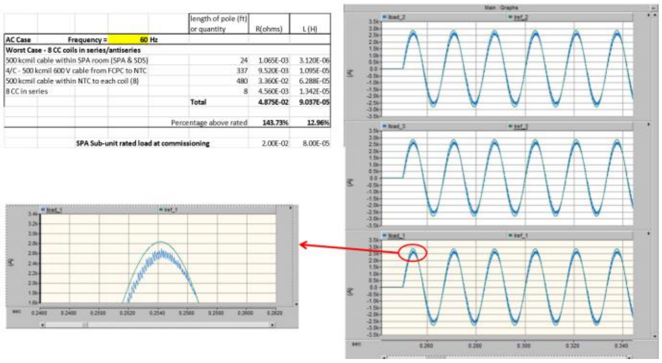
Forensic review of terminator after the test indicates failure in Hi K material at location where it was placed over outside edge of stainless steel.

After these results, Hi-Pot testing proceeded with cold shrink removed which indicated breakdown at the ends. There was no breakdown of MgO insulation observed during any of the testing.

V. PRELIMINARY ASSESSMENT OF SPA OPERATION

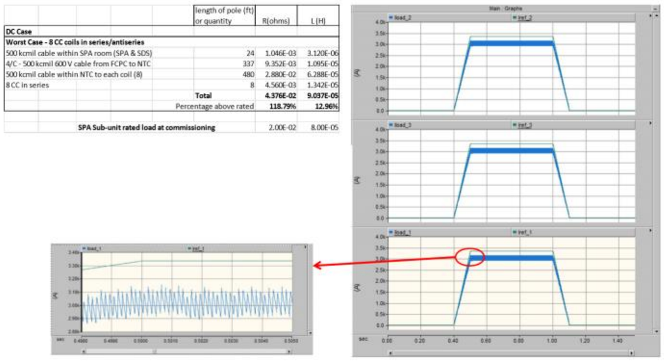
A PSCAD model of the SPAs from 2005 was used for preliminary analysis. The eleven coil interconnection configurations were evaluated to determine those which presented worst case loading to the SPA units. These coil circuit configurations were analyzed for two coil current cases: (See. Fig 13 and 14)

1) *2000 A RMS 60 Hz*
2) *3000 A DC*



	length of pole (ft) or quantity	R(ohms)	L (H)
AC Case **Frequency =** 60 Hz			
Worst Case - 8 CC coils in series/antiseries			
500 kcmil cable within SPA room (SPA & SDS)	24	1.065E-03	3.120E-06
4/C - 500 kcmil 600 V cable from FCPC to NTC	337	9.520E-03	1.095E-05
500 kcmil cable within NTC to each coil (8)	480	3.360E-02	6.288E-05
8 CC in series	8	4.560E-03	1.342E-05
	Total	**4.875E-02**	**9.037E-05**
	Percentage above rated	**143.73%**	**12.96%**
SPA Sub-unit rated load at commissioning		2.00E-02	8.00E-05

Fig. 13 Case 1



	length of pole (ft) or quantity	R(ohms)	L (H)
DC Case			
Worst Case - 8 CC coils in series/antiseries			
500 kcmil cable within SPA room (SPA & SDS)	24	1.046E-03	3.120E-06
4/C - 500 kcmil 600 V cable from FCPC to NTC	337	9.352E-03	1.095E-05
500 kcmil cable within NTC to each coil (8)	480	2.880E-02	6.288E-05
8 CC in series	8	4.560E-03	1.342E-05
	Total	**4.376E-02**	**9.037E-05**
	Percentage above rated	**118.79%**	**12.96%**
SPA Sub-unit rated load at commissioning		2.00E-02	8.00E-05

Fig. 14 Case 2

The worst case loading scenarios for the SPA units are those where the overall inductance of the coil circuit is the highest. In all the proposed scenarios, the mutual inductance due to adjacent NC coils had a neutral (cancelling out) or subtractive effect on the overall inductance. Avoiding the consideration of the coupling of the nearby passive plates represented a worst case, as the corresponding eddy current coupling would have decreased the overall circuit inductance.

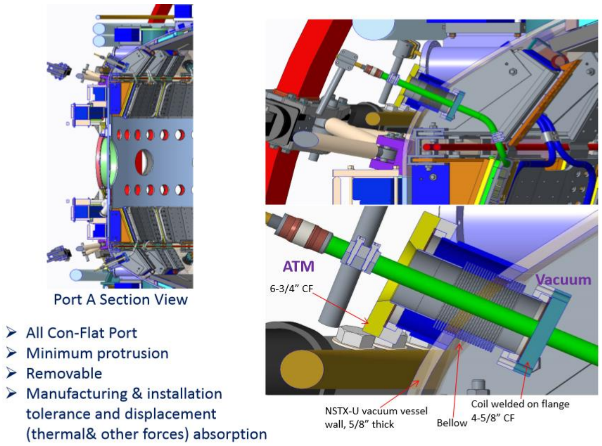
VI. NEW PENETRATIONS DRILLING AND PORT WELDING TECHNIQUES

Each position of every coil will be evaluated for use of either a machined hole or a plasma arc torch hole. The machining will be similar to previous penetration cutting experience in that a set of four 15 degree swivel legs mimicking a ball joint are placed on a 1.25 inch thick CS (copper-steel) alloy plate and use the existing portable milling machine with magnetic base. The plate is placed in a plane which is at right angles to the penetration centerline. The centerline is defined by the Pro E model and a hand held laser is attached to monitor the cut and cur centerline throughout the machining process.

Additional SS (stain steel) structural braces are welded between the CS plate and VV shell. A fly cut is recommended when the angle of attack is reasonable. The machining of highly angled holes is not recommended. Plasma arc cutting should be considered in all cases especially for highly angled cuts.

Plasma arc cut holes require cutting from inside the vacuum vessel, a guiding tool inside the VV and removal if interfering equipment outside the VV, as well as a containment shield to capture the material blow through. (See Fig. 15).

The holes for the MI cabling are not very sensitive to location and condition but cannot be extremely rough and must enclose the theoretically accurate position. Once the hole is made the port nozzle can be accurately positioned by tack welds and monitoring position during welding using a hand held laser and intercept point across the vacuum cessel.ID.

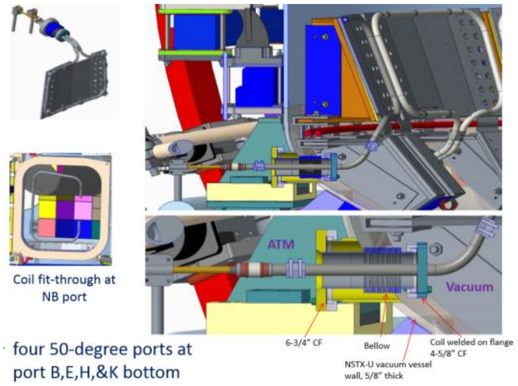


- All Con-Flat Port
- Minimum protrusion
- Removable
- Manufacturing & installation tolerance and displacement (thermal& other forces) absorption

Fig. 15 NCC Coil Feedthrough design for 75 Degree Ports

The nozzle tube is to be inserted through the penetration hole and filet welded from inside the VV and stitch welded outside the VV. Full penetration welds are not required for the NN ports. The excess tube length extending inside the VV is to cut away most likely with a grinding tool and debris contained by a plastic containment mimicking a glove box. (See Fig 16.)

20 ports require 75-degree drill and 4 ports need 50 degree at the vessel bottom.



four 50-degree ports at port B,E,H,&K bottom

NCC Coil Feedout design for 50 Degree Ports

Fig. 16 Port Drill Angle

VII. THERMAL AND ELECTROMAGNETIC ANALYSIS

Analyses of the NC Coils included an initial Assessment of the effectiveness of the coils in the back and in the front of the copper passive plates. As expected, the plates shielded the coil flux if mounted behind the passive plates and reduced their effectiveness when mounted on the surface of the passive plates. Surface mounting was deemed to have an adequate electromagnetic performance. (See Fig.17).

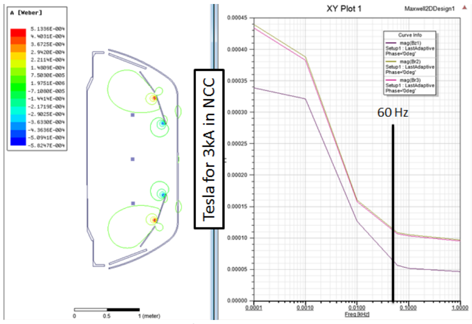


Fig. 17 Frequency Dependence of the Field at the Plasma Provided by the NC Coils

Normal operating Lorentz loads and thermal stresses were addressed. Because of the inertially cooled design of the coils, the fully ratcheted temperature for a run day was used to quantify the peak temperatures in the coil and support structures. Coil Joule heat and the tile surface heat loading were the heat source and conduction and radiation provided the heat sink in the analysis. At the time of the NCC design effort, TZM tiles were planned. (See Fig. 18).

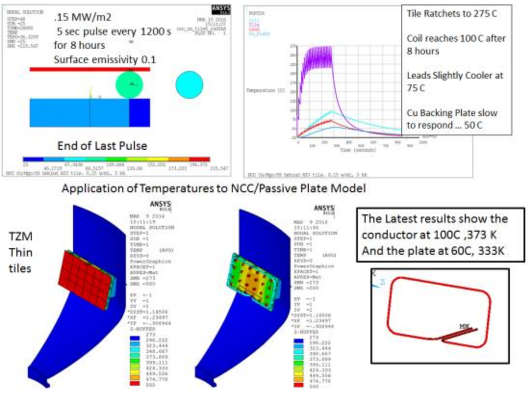


Fig. 18 Temperature Loading

Bake-out also imposed thermal stresses on the coil. The main concern was the relative thermal expansions of the coil, passive plate and vessel shell. The bellows detail in the penetration had to accommodate these motions.

Normal operating loads result from the operating currents crossed with the toroidal and poloidal fields. Many operating modes were postulated, but 2kA at 60 Hz and 3kA DC were representative of many of the current and frequency combinations. (See Fig.19).

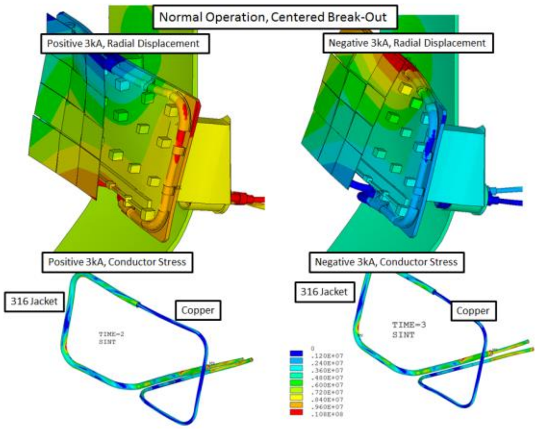


Fig. 19 Displacements and Copper Stresses for Normal Operating Lorentz Loads

The cyclic loading applied to the coil is challenging for the copper used. The stresses must be kept to a minimum to have an acceptable fatigue life. The potential for resonances was addressed. No 60 cycle resonances were found. The first mode was 150 Hz. The steady state Dynamic Load Factor (DLF) was found to be .75 after some initial vibrations with DLF slightly greater than 1.0. For the 2kA 60 Hz case, a cyclic life for the copper of 1e6 was found. The stainless steel jacket life was estimated to be 1e7

Disruption loading was evaluated, with the initial condition of 3 kA DC A VDE and Quench in front of the NCC was analyzed. Plate displacement response to the disruption actually produced the largest stress component. A plate reinforcement had to be added to reduce the stress level in the copper at the terminal extension to a level where 1e6 disruptions could be tolerated. (See.Fig.20)

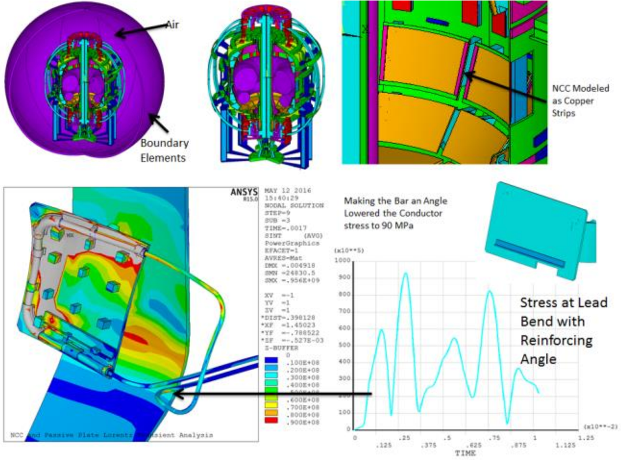


Fig. 20 Conductor terminal bend Stress During a VDE + Quench

VIII. CONCLUSIONS

This publication shows the analysis path to develop a conceptual design for the new In-Vessel Coils. All the options set out and also it is indicated the needed developments that are necessary to continue a successful design for the new coils at the NTSX. Also, a lot of tests were developed with different configurations to make sure the good direction for the right design of the In-Vessel Coils. Further analysis and studies must be performance to finalize the design on the coils, feedthroughs and integration of the total system in the machine.

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The views and opinions expressed herein do not necessarily reflect those of the PPPL Organization.

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