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***TO: DISTRIBUTION***
***FROM: C NEUMEYER***
***SUBJECT: SUMMARY DESCRIPTION OF OH AND PF COILS***

***References:***

***1) NSTX Action Item List , Action Items #1 and #2***

***2) NSTX-CALC-13-002-0, " PF Coil Parameters"***

Attached is a summary description of the OH and PF Coils. In addition, the latest PF coil spreadsheet (version dated 2/3/93) is attached. Details of the spreadsheet are given in the reference (2) calculation.

cc:

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# OH and PF Coils

*General*

The OH and PF coils consist of three new types, and seven types which were formerly in service on the Spheromak-1 (S-1) machine.

| **Designation** | **Source** |
|---|---|
| OH | New |
| PF1a | New |
| PF1b | New |
| PF2a | S-1, EF-1a |
| PF2b | S-1, EF-1b |
| PF3a | S-1, EF-2a |
| PF3b | S-1, EF-2b |
| PF4a | S-1, EF-3a |
| PF4b | S-1, EF-3b |
| PF4c | S-1, EF-3c |

The OH coil is a continuous, constant cross section solenoid winding extending above and below the midplane. All of the other coils consist of symmetric upper and lower pairs, with the exception of PF1b which consists of a lower coil only.

*Electrical Characteristics*

The coils are connected in series groups as follows:

| **PF Circuit** | **Coil Grouping** |
|---|---|
| 1 | OH |
| 2 | PF1a, upper |
| 3 | PF1a, lower |
| 4 | PF1b, lower |
| 5 | PF2a, PF2b, upper |
| 6 | PF2a, PF2b, lower |
| 7 | PF3a, PF3b, upper |
| 8 | PF3a, PF3b, lower |
| 9 | PF4a, PF4b, PF4c, upper & lower |

The OH coil is used for plasma initiation and current drive. The remaining coils are used for plasma equilibrium control and shaping.

Single null plasma configurations as well as vertical position control are enabled via the provision for independent control of the upper and lower PF1a, PF2, and PF3 coils.

PF1b is a special purpose coil used to form the stringent single null X-point configuration which is required for Coaxial Helicity Injection (CHI)

Coil Geometries, circuit resistances, and circuit inductances are summarized in the following tables.

### PF & OH Coil Geometry

| Coil | R (center) | ΔR | Z (center) | ΔZ | Turns | Turn CSA | Fill |
|---|---|---|---|---|---|---|---|
| | (cm) | (cm) | (cm) | (cm) | | (cm^2) | |
| OH | 12.90 | 4.49 | 106.57 | 213.13 | 482.00 | 1.4139 | 0.7120 |
| PF1a | 18.03 | 4.16 | 144.83 | 53.88 | 48.00 | 3.3513 | 0.7177 |
| PF1b | 30.48 | 8.48 | 181.88 | 17.13 | 28.00 | 3.3513 | 0.6457 |
| PF2a | 79.92 | 16.27 | 193.35 | 6.80 | 14.00 | 5.8528 | 0.7409 |
| PF2b | 79.92 | 16.27 | 185.26 | 6.80 | 14.00 | 5.8528 | 0.7409 |
| PF3a | 149.45 | 18.64 | 163.35 | 6.80 | 15.00 | 5.8528 | 0.6928 |
| PF3b | 149.45 | 18.64 | 155.26 | 6.80 | 15.00 | 5.8528 | 0.6928 |
| PF4a | 178.27 | 6.78 | 72.75 | 6.80 | 5.00 | 5.8528 | 0.6349 |
| PF4b | 179.46 | 9.15 | 64.66 | 6.80 | 8.00 | 5.8528 | 0.7525 |
| PF4c | 180.65 | 11.53 | 56.57 | 6.80 | 9.00 | 5.8528 | 0.6723 |

### PF & OH Circuit Resistances

| Circuit | Resistance |
|---|---|
| | (Ω) |
| OH | 9.528E-02 |
| PF1au | 2.798E-03 |
| PF1al | 2.798E-03 |
| PF1b | 2.76E-03 |
| PF2u | 4.14E-03 |
| PF2l | 4.14E-03 |
| PF3u | 8.298E-03 |
| PF3l | 8.298E-03 |
| PF4 | 1.463E-02 |

### PF & OH Mutual Inductance Matrix (mH)

| | OH | PF1au | PF1al | PF1b | PF2u | PF2l | PF3u | PF3l | PF4 | Plasma |
|---|---|---|---|---|---|---|---|---|---|---|
| OH | 1.24E+1 | 6.99E-1 | 6.99E-1 | 3.58E-1 | 2.64E-1 | 2.64E-1 | 2.82E-1 | 2.82E-1 | 4.84E-1 | 1.26E-2 |
| PF1au | 6.99E-1 | 3.76E-1 | 1.95E-4 | 2.26E-4 | 7.23E-2 | 1.35E-3 | 6.04E-2 | 5.29E-3 | 3.90E-2 | 5.22E-4 |
| PF1al | 6.99E-1 | 1.95E-4 | 3.76E-1 | 9.01E-2 | 1.35E-3 | 7.23E-2 | 5.29E-3 | 6.04E-2 | 3.90E-2 | 5.22E-4 |
| PF1b | 3.58E-1 | 2.26E-4 | 9.01E-2 | 5.36E-1 | 1.66E-3 | 1.86E-1 | 6.61E-3 | 1.01E-1 | 4.93E-2 | 4.96E-4 |
| PF2u | 2.64E-1 | 7.23E-2 | 1.35E-3 | 1.66E-3 | 1.98E+0 | 1.03E-2 | 7.31E-1 | 4.11E-2 | 3.08E-1 | 2.68E-3 |
| PF2l | 2.64E-1 | 1.35E-3 | 7.23E-2 | 1.86E-1 | 1.03E-2 | 1.98E+0 | 4.11E-2 | 7.31E-1 | 3.08E-1 | 2.68E-3 |
| PF3u | 2.82E-1 | 6.04E-2 | 5.29E-3 | 6.61E-3 | 7.31E-1 | 4.11E-2 | 5.18E+0 | 1.66E-1 | 1.31E+0 | 9.32E-3 |
| PF3l | 2.82E-1 | 5.29E-3 | 6.04E-2 | 1.01E-1 | 4.11E-2 | 7.31E-1 | 1.66E-1 | 5.18E+0 | 1.31E+0 | 9.32E-3 |
| PF4 | 4.84E-1 | 3.90E-2 | 3.90E-2 | 4.93E-2 | 3.08E-1 | 3.08E-1 | 1.31E+0 | 1.31E+0 | 8.56E+0 | 3.45E-2 |
| Plasma | 1.26E-2 | 5.22E-4 | 5.22E-4 | 4.96E-4 | 2.68E-3 | 2.68E-3 | 9.32E-3 | 9.32E-3 | 3.45E-2 | 9.77E-5 |

In order to satisfy the NSTX operating scenario requirements and range of plasma equilibria, the current ratings of the coil circuits are given in the following table.

**PF & OH Coil Current Ratings Ratings**

| Circuit | Max Current | Max ESW | Max ∫i^2(t)dt | Min Trep | Max Irms |
|---|---|---|---|---|---|
| | (kA) | (sec) | (A^2-sec) | (sec) | (kA) |
| OH | 24.0 | 0.525 | 3.02E+08 | 600.0 | 0.71 |
| PF1au | 15.0 | 5.0 | 1.13E+09 | 300.0 | 1.94 |
| PF1al | 15.0 | 5.0 | 1.13E+09 | 300.0 | 1.94 |
| PF1b | 20.0 | 1.0 | 4.00E+08 | 300.0 | 1.15 |
| PF2u | 20.0 | 5.0 | 2.00E+09 | 300.0 | 2.58 |
| PF2l | 20.0 | 5.0 | 2.00E+09 | 300.0 | 2.58 |
| PF3u | 20.0 | 5.0 | 2.00E+09 | 300.0 | 2.58 |
| PF3l | 20.0 | 5.0 | 2.00E+09 | 300.0 | 2.58 |
| PF4 | 20.0 | 5.0 | 2.00E+09 | 300.0 | 2.58 |

Worth noting is that the repetition period for the full OH (full bipolar current swing) is 600 seconds, whereas the other coils are rated for a 300 second repetition period. The 600 second period is the requirement for the fully inductive NSTX operation, and the 300 second period for partial and non-inductive operation. In the partial inductive mode, the OH will be operated with a unipolar, single swing of current.

The Equivalent Square Wave (ESW) for the OH reflects the 0.5 second flat top requirement for the inductivly driven NSTX scenario. The 1.0 second ESW for the PF1b reflects the short duration of the special x-point required to initiate the CHI. The ESW of the other coils reflect the 4.5 second flat top requirement for partial inductive and non-inductive operation of NSTX, including an allowance for the current rise and fall times.

All of the coils will be driven by series/parallel connected phase controlled thyristor converters at D-site. Individual units are rated 1kV (1012.85V) no-load.

Nominally, the OH coil will be driven by an anti-parallel set of four series connected converter units, for a total voltage of 4kV. To ensure the availability of adequate loop voltage for plasma initiation under all conditions, an additional 2kV will be available if required. Therefore the coil is rated for 6kV operation.

All other coils will be driven at a maximum voltage of 2kV.

All circuits will be grounded via resistors from each terminal to ground, so that (nominally) the maximum voltage to ground will be equal to 1/2 of the voltage applied across the coil terminals. The resistor values (≈ kΩ) will be chosen to limit the ground fault current due to a single ground fault. Therefore the terminal voltages to ground may deviate somewhat from their nominal values,

and the coils must be insulated to ground based on the maximum applied voltage across the terminals.

*Thermal/Hydraulic Characteristics*

All of the coils are water cooled. The inlet water temperature is 10 C for the OH, and 20 C for all other coils.

Due to the relatively long length of the conductor and hence the cooling path in each of the windings which comprise the OH coil, a 400 psi pressure drop is required to obtain the required flow in the outer most layer (the longest cooling path). Flow rates for the other layers are chosen such that the thermal time constants of the cool down of each layer are the same, thereby limiting differential tempertures.

A 100 psi pressure drop provide sufficient flow in the other PF coils.

Based on adabatic temperature rise from the inlet water temperature the final temperatures of the coils due to the rated pulse currents are given in the following table.

**PF & OH Coil Final Temperatures Due To Rated Currents**

| Coil | Final Temp |
|---|---|
| | (deg C) |
| OH | 94.5 |
| PF1a | 75.2 |
| PF1b | 38.3 |
| PF2a | 50.8 |
| PF2b | 50.8 |
| PF3a | 50.8 |
| PF3b | 50.8 |
| PF4a | 50.8 |
| PF4b | 50.8 |
| PF4c | 50.8 |

The OH coil cooling is such that minimal ratcheting of temperature is expected. However, some of the dissipation of heat due to plasma operations (auxiliary heating power) results in a temperature rise of the center stack casing, and a flow of heat inward to the OH coil winding. This occurs primarily in the partial and non-inductive modes (5 second pulse length), when the OH current is unipolar, and $\Delta T$ during a pulse is 40 C or less. In practice, the allowable OH $\int i^2(t)dt$ will be limited as a function of the initial temperature of the coil (at the water outlet) and the center stack casing.

*OH Coil Construction*

The OH coil consists of four layers, wound two-in-hand, for a total of eight windings. There are 962 turns total, and the coil produces a flux swing of 0.62 volt-seconds with a current swing from +24 to -24kA.

Each winding consists of a continuous length (360' max.) of extruded copper conductor (0.394" x 0.630") with circular central cooling hole (0.188" dia), grit blasted and coated with a primer, then insulated with two half-lapped layers of Kapton tape followed by two half-lapped layers of a B-staged epoxy glass tape (Fusa-Fab). Turn to turn and layer to layer insulation thickness is 0.064"

The conductor cross section is extruded with a slightly non-rectangular (keystoned) shape such that after winding the desired rectangular shape and is obtained.

The leads of each winding exit the winding pack at various elevations and toroidal angles in order to facilitate their series connection and connection to the incoming/outgoing bus bars. Thus the heights of the layers vary, with the inner most layer the tallest and the outer most the shortest. The net number of turns above and below the midplane is balanced.

As a result of the winding pattern and the series connection the maximum voltages which appears between turns in the same layer and between layers are 25% and 75% of the total terminal voltage, respectively.

The winding is formed over an inconel tube which serves as a tension spool piece to react axial loads. Therefore the groundwall insulation on the bore of the coil, consisting of three half-lapped layers of Fusa Fab tape, is applied first over the tube prior to winding. The groundwall over the outside of the coil is obtained via taping in the same manner. The groundwall over the ends of the coil is obtained using glass reinforced epoxy end caps. The insulation at the ends is carefully tailored to ensure a homogeneous groundwall insulation. After cure the groundwall is painted with a conducting varnish to form an electrostatic shield (ground plane).

Total insulation thickness to ground (turn plus groundwall) is 0.086".

Insulation electrical performance is summarized in the following table.

## OH Electrical Insulation Performance

| | Max Operating Voltage | Insulation Thickness | Max Operating Stress | Test Voltage |
|---|---|---|---|---|
| | (volt) | (mil) | (volt/mil) | (volt) |
| Terminal-Terminal | 6077 | 64 | na | na |
| Turn-Turn | 1520 | 64 | 24 | 4000 |
| Layer-Layer | 4560 | 64 | 71 | 10000 |
| Turn-Ground | 6077 | 86 | 71 | 13000 |

*PF1a/1b Coil Construction*

The PF1a and PF1b coils are 2 layer, 48 turn and 4 layer, 28 turn coils, respectively.

Each winding consists of a continuous length of extruded square copper conductor (0.787" x 0.787") with circular central cooling hole (0.3543" dia), grit blasted and coated with a primer, then insulated with two half-lapped layers of Kapton tape followed by two half-lapped layers of a B-staged epoxy glass tape (Fusa-Fab). Turn to turn and layer to layer insulation thickness is 0.064".

Groundwall insulation consists of three half lapped layers of Fusa Fab. Total insulation thickness to ground (turn plus groundwall) is 0.086".

Insulation electrical performance is summarized in the following table.

## PF1a/1b Electrical Insulation Performance

| | Max Operating Voltage | Insulation Thickness | Max Operating Stress | Test Voltage |
|---|---|---|---|---|
| | (volt) | (mil) | (volt/mil) | (volt) |
| PF1a Terminal-Terminal | 2025 | 64 | na | na |
| PF1a Turn-Turn | 42 | 64 | 0.7 | na |
| PF1a Layer-Layer | 2025 | 64 | 32 | na |
| PF1a Turn-Ground | 2025 | 86 | 24 | 5000 |
| PF1b Terminal-Terminal | 2025 | 64 | na | na |
| PF1b Turn-Turn | 72 | 64 | 1.2 | na |
| PF1b Layer-Layer | 1012 | 64 | 16 | na |
| PF1b Turn-Ground | 2025 | 86 | 24 | 5000 |