NCSX
Diagnostics Specification
External Saddle Loops
NCSX-CSPEC-31-01-00
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Record of Revisions

Revision	Date	Description of Changes
Rev 0	9/6/2006	Initial issue

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1 SCOPE

The National Compact Stellarator Experiment (NCSX) is an experimental research facility that is to be constructed at the Department of Energy's Princeton Plasma Physics Laboratory (PPPL). Its mission is to acquire the physics knowledge needed to evaluate compact stellarators as a fusion concept, and to advance the understanding of three-dimensional plasma physics for fusion and basic science.

In support of that effort NCSX will have an extensive set of external magnetics diagnostics. These include flux loops and voltage loops to be installed on the exterior surface of the vacuum vessel. Data from these and other sensors will be used for plasma control and to constrain magnetic equilibrium reconstructions. NCSX is currently under construction at the Princeton Plasma Physics Laboratory. The ex-vessel flux and voltage loops must be installed during machine construction because they will ultimately be trapped in the space between the vacuum vessel and the modular coil support shell. Modeling was performed to determine the optimum size and placement of the ex-vessel flux loops. Designs have been developed and components have been fabricated for installation of these magnetic measurement loops to start shortly. The flux loops must be accurately positioned and they must be reliable. The loops will be exposed to the vessel bake out temperature and though thermally insulated, are surrounded by a cryogenic environment. The loops must operate reliably for the lifetime of NCSX.

2 DEFINITIONS AND APPLICABLE DOCUMENTS

2.1 Definitions

2.1.1 Flux Loop

A flux loop is a continuous length of insulated coaxial cable having a metal sheath, arranged into two turns with the exiting leads twisted from the loop up to and inside a junction box that is outside the cryostat boundary where the transition is made to conventional shielded cable which is then run to the Diagnostics electronics.

2.1.2 Voltage Loop

A voltage loop is a continuous length of insulated coaxial cable having a metal sheath and arranged into a toroidal single turn. There are four loops, they are generally parallel, and are 360°. Each field period contains 120° of the loop. The complete loop is formed when the three field periods are assembled. There are excess lengths of cable on the end of each field period. These lengths are twisted starting at the vessel surface and when operational will terminate in junction boxes (JB) outside the cryostat. One of the JBs will be selected to use conventional cables to connect each of the four loops to Diagnostics electronics. Prior to operation the twisted leads will be coiled inside a non magnetic protective box inside the cryostat boundary.

2.2 Applicable Documents

- Field Period Assembly Station 1 Dimensional Control Plan (NCSX-PLAN-FPA1DC-0)

- Field Period Assembly Station One Procedure (NCSX-PLAN-FPADC) – latest revision
- Field Period Assembly Station One Procedure (D-NCSX-FPA-001) – latest revision
- Field Period Assembly Station One External Saddle Loop Installation Procedure (D-NCSX-FPA-002) – latest revision
- Drawings:

Table 2-1 External Saddle Loop Drawings

Drawing Number	Title	Revision
SE310-030-1.pdf	Magnetic Loop Arrangement Drawing	0
SE310-030-A-Q.drw, Sheets 1-15	Magnetic Diagnostics, Magnetic Loops Series A-Q	0
SE310-030-TH0-1.drw, Sheets 1-2	Magnetic Diagnostics, Magnetic Loops Series TH0-1	0
SE310-030-TH0-2.drw, Sheets 1-2	Magnetic Diagnostics, Magnetic Loops Series TH0-2	0
SE310-030-TH0-3, Sheet 1	Magnetic Diagnostics, Magnetic Loops Series TH0-3	0
SE310-030-TH180	Magnetic Diagnostics, Magnetic Loops Series TH-180	0

3.0 REQUIREMENTS

3.1 Overall Design Requirements

Provide a total of 225 flux loops and 4 voltage loops, attached to the surface of the vacuum vessel.

3.1.1 Distribution of Flux Loops

- 205 flux loops are to be distributed among the 3 field periods defined as the Random Distribution (Table 2-1), including the inner and outer Toroidal arrays (10 per field period). Six of these are to be installed on the Stellarator symmetry points (theta 0 and 180) and are referred to as "Symmetry Loops”.
- 16 flux loops are to be arranged into a continuous poloidal array (Table 2-1) on one of the Field Period (FP) spacers. Two of these are to be installed on the Stellarator symmetry points (theta 0 and 180) and are referred to as "Symmetry Loops.”
- 4 flux loops are to be placed on the remaining FP spacers (Table 2-1), on the Stellarator symmetry points (theta 0 and 180) and are referred to as "Symmetry Loops.”

3.1.2 Distribution of Voltage Loops

- The four voltage loops are run in a general toroidal direction 360º with some poloidal excursions but having a substantial poloidal spacing between the four loops

3.2 Flux Loop Geometry Requirements

The physics group calculated the unique geometry of, and location of the 205 flux loops located on the three field periods (FP). The remaining 20 flux loops are located on the FP spacers (3.1.1). This data was converted into Pro E models so that winding templates could be fabricated, permitting the accurate formation and location of the loops. The signal strength generated in a measurement loop is small. Therefore the conductor is to be electrostatically shielded, and stray magnetic fields and RF pickup are to be limited.

The following are guidelines for machining and locating the flux loops. The NCSX Field Period Assembly Station One Procedure (D-NCSX-FPA-001) (2.2) and the associated drawings (Table 2-1) contain specific fabrication, installation, and assembly details.

- Templates
  - Use a thin (3.5) accurately machined template fitted to the vessel contour as a cable winding form, for the hand formation of an external flux loop. The material thickness is to be thin enough to permit easy and accurate hand contouring to match the local vessel surface, yet thick enough to permit winding the cable with no deflection or distortion.
  - Accurately locate the templates. Firmly hold the templates in place so that there is no displacement, until a loop is formed and anchored. After the loops are completed the templates are to be removed.
  - Create a flat development drawing of the contoured templates to permit fabrication by simple means such as water jet machining.
  - Select a material for the templates which is pliable, yet sufficiently stiff to retain the contoured shape.
  - Provide the winding templates with indents to aid installation of hold down clips, and provide a minimum bend radius of 4 times the cable OD at the corners.
  - Provide sufficient locator points and geometry features on the templates to aid installation. This is to be completed by design drafting in the Pro E model. Provide a minimum of one locator point per side.
  - Use accurate measurement systems to locate the templates locator points. Use a system capable of an accuracy of better than 0.010 inch. A Romer Arm is one acceptable system.
- Hold Down Clips
  - Use thin metal hold down clips to secure the loop cable to the vessel surface suitable for spot welding to inconel 625 (a minimum of 4 spot welds on each side). The clip and vessel materials are to be compatible. The magnetic permeability of the clips and spot welds is to be less than 1.02.
- Cable, Loops, Leads and Other Geometry Requirements

- The cable should have a metal sheath to provide electrostatic and RFI shielding. The cable is to be sufficiently robust to limit physical damage during machine assembly and operation. Sections of the cable may be in contact with a 350ºC surface or will be close to the welding of the vessel field periods or nozzles. The sheath and conductor material are to reasonably match the coefficient of thermal expansion of the vessel. The signal generated by the flux and voltage is small (milliamp and millivolt ranges) so there is no specific electrical requirement for the center conductor. The sheath is in direct contact with the vessel and the conductor will connect to isolated electronics. Therefore the sheath to conductor isolation is to be 300 volts or greater.
- The loops must in general fit under the Heating / Cooling tubing. Limit the location and number of radial build deviations.
- The exiting leads are to be hand twisted. Twist the exiting leads with a maximum ¾ inch pitch to limit stray field pickup. The twisted leads are to be secured with spot welded straps similar to those used to secure the two turn loops.
- Limit the general height build to 1/8 inch. There will be a limited number of locations where the 1/8 inch build must be exceeded, but the location is to be well away from a Cooling/ Heating line.
- Provide robust junction boxes (JB) to protect the cable before and after terminations are completed. The purpose of the JBs is to limit RFI pickup. The JBs are to be large enough to permit coiling of the leads inside before the TBs and circuit boards are installed. The JBs magnetic permeability is to be less than 1.02.
- The absolute minimum bend radius of the coaxial cable is 2 times the sheath OD, in no case is it to be smaller. In general the minimum radii are to be 4 times the OD. The size of the bend radius impacts the useful cable life. The cable runs on the vessel surface are not accessible after NCSX is assembled, therefore attention to the field cable configurations is important.
- After completion, the flux loops are to be checked for continuity of the center conductor and for electrical isolation between the conductor and sheath.

3.3 Voltage Loop Geometry Requirements

The following are guidelines for locating the voltage loops. The NCSX Field Period Assembly Station One Procedure (D-NCSX-FPA-001) (2.2) and the associated drawings contain specific fabrication, installation, and assembly details.

- The four voltage loops shall be single turn loops. The Voltage Loops are toroidal runs and occupy the three field periods as shown on arrangement drawing (Table 2-1). The cable shall be the same as that used for the External Flux Loops. The Voltage Loops will cross over the Flux Loop twisted leads and run between the Flux Loops and under the Heating/Cooling lines. The Voltage Loops are to be secured to the vessel surface in a similar manner to that used for the Flux Loops. The Voltage Loops will be completed when the vessel field periods are brought together and welded. The adjacent leads will be twisted to a maximum ¾ inch pitch as the field periods are being joined. The twisted leads are to be sufficiently long to preclude splicing inside the cryostat. The loops are to be coiled into a protective box for initial NCSX operations. The magnetic permeability of the protective box is to be less than 1.02. When placed into operation, the twisted cables are to exit the cryostat with the Co Wound loops through the cryostat insulating panels, to a JB for hook up to Diagnostic electronics.

- The absolute minimum bend radius of the coaxial cable is 2 times the sheath OD, in no case is it to be smaller. In general the minimum radii are to be 4 times the OD. The size of the bend radius impacts the useful cable life. The cable runs on the vessel surface are not accessible after NCSX is assembled, therefore attention to the field cable configurations is important.
- After completion, the voltage loops are to be checked for continuity of the center conductor and for electrical isolation between the conductor and sheath.

3.4 Physical Characteristic Requirements

The following describe the physical characteristics of the external saddle loops:

- The cable is to be coaxial 0.059 inch OD sheath with compressed powder MgO insulator and 0.020 inch diameter conductor, equivalent to ARI Industries.
- The twist pitch of the exiting leads is to be less than ¾ inch but more than ½ inch.
- The templates are to be 0.043 inch thick and machined with the central portion open producing approximately a one inch wide irregular ring. The corner radii in general are not smooth curves but a curve made of faceted straight lines which is an artifact of the CAD system. The minimum radius within the corner construct is not less than 0.25 inch. One half by three eights inch indents are to be provided for placement of pre bent hold down clips on the cable.
- In general do not exceed a 10 inch spacing between the cable hold down clips of the loops and twisted leads. There should be a minimum of 4 spot welds clips on each side of each clip.
- The Saddle Loop Junction Boxes shall be 3.5 inch by 4 inch by 8 inch plates held together with flat head screws to provide the maximum possible access for termination of the leads. The top and bottom plates are 0.25 inch thick, the side plates are 0.090 inch thick and the auxiliary strain relief plate is 0063 inch thick. Seal the edges of the box with ½ inch wide foil tape with conductive adhesive, 0.0035 inch thick when ready for operation of the loops.
  - The ends of a cut cable shall be sealed with Aero Seal from ARI Industries or equivalent, shortly after cutting, to prevent moisture in the ambient air from migrating into the MgO insulation.

3.5 Material Requirements

The following are the material requirements for the external saddle coils:

- Coaxial cable sheath and center conductor shall be 600 series inconel and the electrical insulator shall be compressed powder MgO.
- Templates are to fabricated from 110 electronic grade copper annealed to 1/8 hard.
- Cable hold down clips are to be fabricated and preformed of 316 SS, 0.005 inch thick with a magnetic permeability of less than 1.02 after forming.
- Template temporary hold downs are to be fabricated of 316 SS, 0.010 inch thick with a magnetic permeability of less than 1.02 after forming.
- Junction boxes (JB) shall be fabricated of 6061 T6 aluminum with a 316 SS auxiliary plate for spot welding strain relief clips.
- Copper foil tape with conductive adhesive shall be used on all JB open edges. This is to be installed after the loops become operational.

3.6 Installation Requirements

An installation procedure shall be prepared to detail each specific installation step. The following are the installation requirements for the external saddle coils that should be incorporated into this installation procedure. **(NOTE: If there is a conflict between the installation procedure and this specification, this specification shall prevail)**:

- The locator points for each template are listed on the arrangement drawing (Table 2-1).
- The fabricated loop templates shall be installed as per the guidelines and procedures specified in the associated drawings (Table 2-1) and the NCSX Field Period Assembly Station One Procedure (D-NCSX-FPA-001) (2.2) using a precision measurement device with the VeriSurf software. Each template position is defined by its multiple locator points (ideal) listed in the table of the arrangement drawing (Table 2-1).
- The ideal surface data and the as built and measured vessel surface data should be input to the metrology software. Minimize the distance between an ideal point and a final selected surface point, while keeping the difference in the local x-y coordinates to less than 0.160 inch for the general loops and 0.020 inch for the symmetry loops. A secondary requirement for a symmetry loop is that it be equidistant from the center of the NB port (theta = 0) and the corresponding point at the inner center (theta=180), with a local x-y coordinate difference of less than 0.020 inch, if the as built dimensions of the vacuum vessel do not permit the first requirement to be met.
- Mark the locator points with a bluing compound or equivalent and lightly scratch the position on the vessel surface. Do not center punch since there is significant local distortion from this operation.
- Contour the templates to the vessel surface by hand. All templates are to be installed before winding the cables except where nesting requires the installation of the cable on one template before the second one is installed.
- Determine the location of the Heating / Cooling tube weld studs and mark the footprint of the H/C tube mounting pads. Position them to avoid the flux loops, with a minimum clearance of 1/4 inch.

- Determine the routing of the voltage loops per the associated drawings (Table 2-1) and mark the paths on the vessel.
- Determine the path of the flux loop exiting leads and mark on the vessel.
- Determine the length of cable required by measurement leaving approximately 18 inches of excess length protruding from the JB and wind the cable into the loop configuration. Clean the cable sheath thoroughly with alcohol and the vessel surface at the hold down locations.
- Use a material that is flexible but not elastic such as stranded wire to measure the length of cable required for a specific loop. Determine the length of cable required for a specific loop by measurement. The circumferential length is determined by measuring the template perimeter (P) and multiplying by 2 (two turn coil). The twisted pair length (lg) is determined by measuring the path marked on the vessel surface up to and into the JB, adding 18 inches and multiplying by 2.8. The total minimum length of coaxial cable needed to form a two turn loop and a twisted pair into the JB, with sufficient length to strain relieve the cable and terminate them into the terminal blocks is, L = 2(P) + 2.8 (lg+18).
- Twist the leads up to, but not into or beyond, the entrance of the JB. The cable is be smooth and leads parallel through the rubber seal. Identify the cable using the color code provided in the arrangement drawing (Table 2-1) on the cryostat side and the JB side.
- Maintain the polarity sense (clockwise looking at the template) if practical. If a counterclockwise polarity loop must be installed, document the loop tag number. Special pens will be provided to color code the loops. Temporary 316 SS hold down clips may be used while nesting the twisted lead runs.
- Test the continuity of each loop and the resistance between the conductor and sheath after each loop is formed. List the values and document as each loop is completed.
- The layout drawing will identify the predrilled holes be used for the cables exiting the cryostat through the 2-3/4 inch Conflat Flange (CF) and JB. The predrilled holes for the ¼ inch threaded fasteners will permit orienting the JB properly.
- Assemble the CF, rubber seal, and JB, but do not tighten the ¼ inch threaded fasteners until all the cables are pulled into the JB. The ¼ CF hardware is tightened only after all the cables are pulled into the JB.The cables should be stress relieved within the JB, using a stainless steel plate and stainless steel shims stick. The rubber seal will form the gas boundary around each cable. The JB must be oriented properly on the horse collar.
- Follow the installation procedure to install the cables. Ensure that the cables are identified by color as per the drawing and that the rubber seal is punctured to permit cables to penetrate. After all cables are pulled into a JB, the end should be square cut to a length of 15 inches and the ends immediately sealed with Aero Seal.
- Assemble the JBs. A JB shall consist of flat plates with no cut outs for the D subminiature connector and there are to be no terminal blocks / circuit boards installed at this time. The JB is to protect the lead cables during machine assembly and operations. The terminations are to be completed at a later date. When the flux loops become operational the JB edges are to be covered with copper foil with conductive adhesive.

- Wipe the cable clean with alcohol. The area of the vessel where the spot welding occurs should also be cleaned with scotch bright or light sanding and wiped clean with alcohol.
- Measure and document the as built geometry of the flux loops. Each flux loop position and geometry is to be measured by using either a Romer Arm with a small tip or a laser tracker and tracing the interface (groove) between the two turns. The measurement should be made a minimum of every one inch. In addition the triangular open area, formed at the point where the twisting of leads start, is to be measured and documented as a continuous geometry. The measurements should be logged into a table of xyz coordinates which can be read by the Physics Group. The base coordinates of the machine shall be used and data saved on a FTP site for later reference.

4 QUALITY ASSURANCE PROVISIONS

PPPL QA is to examine the installation, including, at a minimum the following verifications:

- Visually examine the loop cable for obvious defects and conformance with the requirements of this specification and the arrangement drawing (Table 2-1).
- Examine a 10% sampling of the hold down clips to ensure that magnetic permeability is less than 1.02.
- Examine spot welds on the hold down clips for number and visual appearance and a 10% sample to ensure that the magnetic permeability is less than 1.02.
- Measure the as built geometry and location of each of the 225 loops. The data is to be logged on the FTP site set up for this purpose as xyz coordinates.
- Verify that tagging of each cable is in conformance with the requirements on the arrangement drawing (Table 2-1).
- Check and document each cable for the continuity and resistance between conductor and sheath and ground check all cables.. Record these values for later reference.
- Check that all loops are installed, including the voltage loops, with twisted leads run up into the JB, that the gas seal is made, that there is a sufficient service loop in JB, that the cable end is sealed an, and that the JB assembled.