Rogowski Loop Designs for NSTX *

B. McCormack, R. Kaita, H. Kugel, R. Hatcher

Princeton Plasma Physics Laboratory, Princeton University
P. O. Box 451, Princeton, NJ, 08543

Abstract - The Rogowski Loop is one of the most basic diagnostics for tokamak operations. On the National Spherical Torus Experiment (NSTX), the plasma current Rogowski Loop had the constraints of the very limited space available on the center stack, 5000 volt isolation, flexibility requirements as it remained a part of the Center Stack assembly after the first phase of operation, and a +120°C temperature requirement. For the second phase of operation, four Halo Current Rogowski Loops under the Center Stack tiles will be installed having +600°C and limited space requirements. Also as part of the second operational phase, up to ten Rogowski Loops will installed to measure eddy currents in the Passive Plate support structures with +350°C, restricted space, and flexibility requirements. This presentation will provide the details of the material selection, fabrication techniques, testing, and installation results of the Rogowski Loops that were fabricated for the high temperature operational and bakeout requirements, high voltage isolation requirements, and the space and flexibility requirements imposed upon the Rogowski Loops. In the future operational phases of NSTX, additional Rogowski Loops could be anticipated that will measure toriodal plasma currents in the vacuum vessel and in the Passive Plate assemblies.

I. INTRODUCTION

The Rogowski Loop is one of the most important diagnostics from a plasma current measurement and control aspect of tokamak operation. A loop is a multi-turn uniformly wound solenoid having a uniform cross-sectional area and completely wraps around the current to be measured. The winding operation introduces a resultant one-turn advance which can be cancelled out by an identical reverse winding overlaid or a single "return" loop. The NSTX designs used the single "return" loop cancellation method.

The Rogowski Loop output voltage equation is:

$$V_o = 2 \times 10^{-3} \frac{nA}{R} \frac{dI(t)}{dt}$$

where V_o = the loop output voltage in volts
n = number of winding turns
A = cross-sectional area of individual turn (cm^2)
I (t) = current (megamps)
R = Rogowski Loop major radius (cm)
t = time (seconds)

Another way of expressing the Rogowski Loop output voltage equation is:

$$V_o = 0.03192\ nA \frac{dI(t)}{dt}$$

where V_o = the loop output voltage in volts
n = turns per inch
A = mandrel cross-sectional area in inches
I (t) = current (megamps)
t = time (seconds)

The constant takes into account metric/English conversions while the equation form highlights the direct relationship of turns and cross-sectional area to resultant output voltage.

II. PLASMA CURRENT ROGOWSKI LOOP

A. Specifications

The plasma current Rogowski Loop had the requirements to fit in the approximate 0.135" space between the inner diameter of the Center Stack casing insulation and the OH Coil outside diameter. It would be measuring Mamp plasma currents with a maximum dIp/dt of 5 Mamp per second. The electrical isolation of 5000 volts between Center Stack and vacuum vessel along with a 120°C-temperature compatibility were additional requirements. Two loops were to be installed and the installation required extreme flexibility.

B. Design and fabrication details

Due to the flexibility and temperature requirements, Teflon was chosen as the mandrel material. In order to obtain a reasonable output voltage, the mandrel shape was selected to be a rectangular with the dimensions of 0.048" x 1.10" with rounded edges.

The winding pitch of 77 turns per inch was selected using an AWG No. 30 gauge, Class 220 (220°C rating), heavy polyimide-coated copper magnet wire. The pitch was also chosen to maximize output voltage.

The length of the plasma current Rogowski Loop was conservatively estimated to be approximately 34' as it traveled inside the Center Stack casing, enclosing one poloidal field coil, and under the remaining poloidal field coils. Also, the loops would be required to stand off from the vacuum vessel due to the +350°C bakeout requirement.

The Teflon was procured as a 4' x 8' x 1/16" sheet and cut into 8' x 1/8" wide strips. The strips were pulled through progressive dies to achieve a 1.1" wide by 1/16" thick mandrel shape.

A preliminary minimum length of 37' for the mandrel length was established to allow for the winding operation. In order to achieve the 37' minimum length using the 8' long Teflon strips, each end was bias cut at 45° and machined to half thickness for 2". The end machining was configured to allow one piece to be end-fitted with the next strip. After the machining, the Teflon strips were sodium ammonia solution etched to prepare the Teflon for adhesive bonding. The etching process colors the Teflon a dark brown, with negligible size or flexibility change.

The adhesive used was a 3M, Scotch-Weld Epoxy Adhesive, #2216 B/A Gray. Alignment/clamping fixtures were used and the vendor cure instructions were followed.

As mentioned above, the NSTX designs used the single "return" loop cancellation method. To incorporate the single "return" loop, a groove was machined along the long axis of the mandrel to enable the single "return" winding to be recessed inside the mandrel (Fig. 1). At the same time, both sides of the mandrel were machined equally to reduce the mandrel thickness to 0.049"+0.000/-0.002.

The winding of three Plasma Current Rogowski Loops was achieved by first installing the single AWG No. 30 magnet wire "return" winding and covering the wire with 0.002" thick Teflon tape. The next step was to "fly wind" the "main" winding at a 77 turns per inch pitch. Splices were permitted and were performed per a splicing procedure; any splices were placed along the 0.048" edge and locally taped in place. One assembly had three splices and the other two did not have any splices. Winding turn "crossovers" were permitted; one unit had one and the other two did not have any "crossovers." The two magnet wire self leads at each end would be terminated in the field installation.

The first design specified a one-half lap wrap of 0.002" thick Teflon tape for the loop section of approximately 8ft which was inside the Center Stack Casing and the remaining length at both ends received a one-third lap wrap of 0.002" thick Teflon tape. First article testing revealed a 5000 volt breakdown in the one-half wrap section.

The insulation design was changed as follows:

a) remove the one-half lap wrap of 0.002" thick Teflon tape from the Center Stack Casing section for thickness build-up reasons;
b) install a 0.002" thick kapton tape over the entire loop, one-third-lap wrap on the end sections and one-half lap wrap in the Center Stack Casing section. All modified loops passed the 5000 volt insulation testing.

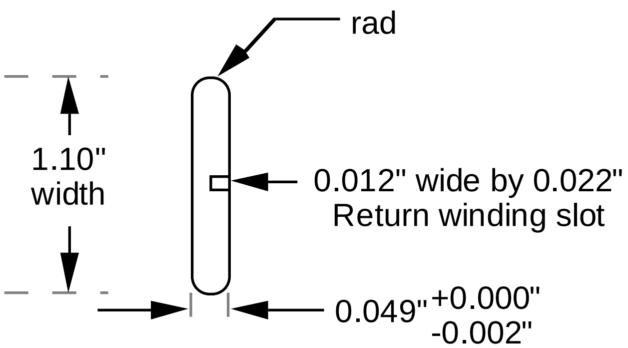

Fig. 1. Cross-sectional view of plasma current Rogowski mandrel.

C. Test Results

A Rogowski Loop test setup (Fig. 2) was configured to perform scale factor measurements.

The average tested scale factor was:

$$V_o = 0.198 \frac{dIp(t)}{dt}$$

where V_o = the loop output voltage in volts
Ip(t) = plasma current(megamps)
t = time(seconds)

The tested scale factors were approximately 8% higher than the calculated scale factor due to the inaccuracy of establishing the effective mandrel thickness. This is a combination of the Teflon tape thickness and the magnet wire conformance to the mandrel. The average resistance of the main winding was an 805 ohms with an average inductance of 6.4 μhenrys; the average resistance of the return winding was a 4.5 ohms with an average inductance of 85 μhenrys.

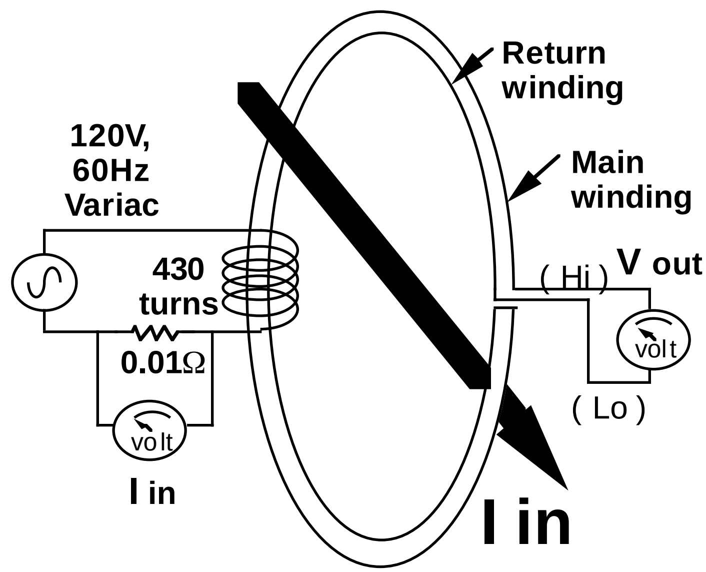

Fig. 2. Rogowski Loop Test Setup.

D. Installation

The first phase of the field installation was positioning and attaching the two loops along the vertical axis of the OH Coil. The angular orientation was established to be clear of port covers and the linear orientation was established to place the termination at a convenient lower dome location. The loops were Kapton taped to the OH Coil. Voltage isolation tests at 5000 volts were successful.

The second phase of the field installation was the lowering of the Center Stack Casing over the thermally insulated OH Coil Assembly, which included the two loop assemblies. The loops were pulled up through the casing and had to have the flexibility to pass two 90° bends around the Poloidal Field Coil, PF1A.

The third phase of the field installation was the lowering of the Center Stack Assembly through the vacuum vessel assembly for the attachment to complete the vacuum vessel. The loops had to be tightly coiled up and "tucked" away to clear the vacuum vessel diameters.

The final phase of the field installation was the uncoiling of the loops and the welding of steel brackets to support the loops in insulated clamps. This spaced the loops away from the vacuum vessel approximately four to six inches in most areas and provided positional stability. In close areas, additional Kapton sheet and tape was installed for protection purposes.

The loop assemblies had been purposely wound longer than required. At a bracket-supported junction, the length was reduced to that required at the final installation and the appropriate terminations to the field cabling were made. The resultant average loop length was 34'. The average resistance of the complete loop was a 729 ohms with an average inductance of 4.3 μhenries.

E. Subsequent Installations.

During the first brief operational run period, the Rogowski Loops were successfully used to measure plasma currents up to 300kA. After this time, the Center Stack Assembly was withdrawn from the vacuum vessel to facilitate interior assembly work. Three strips of copper foil shielding were applied to both exposed ends (outside the Center Stack region) along the length, leaving one edge exposed. The copper foil was terminated to field cable shielding, which is connected to the instrumentation rack ground. The Center Stack Assembly has been re-installed and the Rogowski Loops re-terminated.

III. HALO CURRENT ROGOWSKI LOOP

A. Specifications

The halo current Rogowski Loops are designed to detect currents flowing through the Center Stack as a function of plasma location They had the requirements to fit under the Center Stack carbon tiles in a 0.400" radial by 1.000" axial space. The temperature requirement was 600°C and four loops were to be installed around the 20" casing diameter. The assembly under the tiles and around the casing required flexibility.

B. Design and fabrication details

Due to the temperature requirement, a ceramic webbing was chosen as the mandrel material. This form of ceramic also provided the flexibility required to fit behind the Center Stack carbon tiles. The webbing material chosen had a nominal 0.125" by 0.750" cross-sectional area. Based upon the space allocated and the desire for as high an output signal as possible, three sections were bonded together using a high temperature adhesive, Fortafix Fiborclad. In order to maintain the required flexibility, the adhesive was applied in approximate 1/4" vertical strips across the width at one inch increments; this procedure maintain sufficient flexibility. The average resultant mandrel cross-sectional area was 0.259" by 0.747" (see Fig. 3).

The same winding pitch of 77 turns per inch as the plasma current loops was used. Due to the high temperature requirement, a ceramic insulated AWG No. 30 magnet wire, fabricated by Cermawire, was used. The ceramic insulation has a degree of porosity and a significant coarseness that must be considered in the Rogowski Loop fabrication.

A winding length of ~66" and a mandrel length of ~69" was chosen to allow for trimming back to fit the 20" Center Stack Casing diameter. The "return" winding was installed along one of the edges and the "main" winding was "fly wound" over the "return" winding; the result was a continuous winding loop.

Early tests revealed a design problem; the "return" winding was shorting out to the "main" winding. The rework decision was to remove the "return" winding from under the "main" winding.

The next step was to establish the loop length with an insulation wrap that would result in a close fit around the diameter with the ends nearly butting. The actual magnet wire winding was set back from the mandrel ends by 1/8" to 1/4". Once established, the winding ends were secured with a coating of the Fortafix adhesive. One of the field leads, Awg No. 24 Quartz insulated leads, was welded to one of the ceramic insulated magnet wire self leads and routed along the mandrel edge to serve as the "return" winding. The other field lead was welded to the other self lead.

Due to the temperature requirement, welding was chosen to make the connection between the Rogowski Loop and the field cable. There is no requirement to "strip" the ceramic insulation or prepare the nickel coated copper field cable. The termination connections were positioned along the edge of the winding/mandrel assembly. The welded joint and the field cable were installed inside a 1200°F fiberglass sleeving which was continued up to the vacuum feedthru connector.

To protect and insulate the ceramic winding from the carbon tiles, a Nextel one-inch ceramic tape was one-half lap wrapped around the winding/mandrel assembly. The wrap was applied over the welded joints, the "return" winding (field cable/sleeving), and the "main" winding connection; the wrapping served as a strain relief for the field to magnet wire connections. Both tape ends were ends were secured with a coating of the Fortafix adhesive.

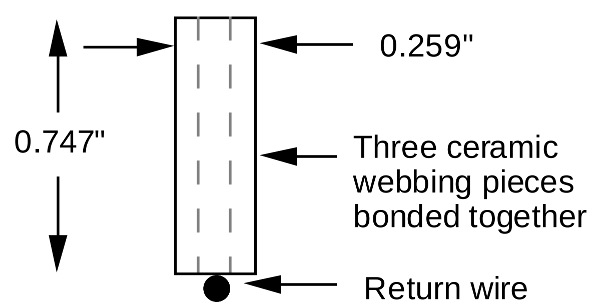

Fig. 3. Cross-section of halo/eddy current Rogowski mandrels.

The average mandrel cross-sectional area after the wrapping process was 0.360" by 0.940" with individual locations approaching the 0.400" by 1.000" carbon tile cutout.

C. Test Results

The Rogowski Loop test setup (Fig. 2) was used to perform the scale factor measurements.

The average tested scale factor was:

$$V_o = 0.476 \frac{dIp(t)}{dt}$$

where V_o = the loop output voltage in volts

I(t) = halo current (megamps)

The tested scale factors were identical to the calculated scale factor. The average resistance of the loop with approximately 7' of field cable was 113.3 ohms with an average inductance of 2.5 millihenrys.

D. Installation

The Center Stack Assembly has seven rows of tile on the larger diameter upper and lower portions. Halo Current Rogowski Loops were installed between the second and third row, and also between the fourth and fifth rows of tiles; this was done on the top and bottom portions.

The installation process required the field leads to be installed into a cable channel machined in the carbon tiles and run to a feedthru tube and connector. At the same time, the mandrel/winding assembly was installed behind one of the rows of tiles. The loop was closed in by the installation of the next row of tiles.

IV. EDDY CURRENT ROGOWSKI LOOP

A. Specifications

The eddy current Rogowski Loops are intended to measure the distribution of currents induced in conducting structures surrounding the plasma. They had the requirement to be able to wrap around the Primary and Secondary Passive Plate assemblies. The temperature requirement was 350°C and four loops would be required for the top Primary Passive Plates and one for the top Secondary Passive Plates; a mirror image complement would be installed on the bottom Passive Plates.

B. Design and installation details

Even though the temperature requirement was lower, the same ceramic webbing mandrel used on the Halo Current Rogowski Loop was chosen and design fabrication was the same; the only difference was the winding/mandrel lengths. This mandrel form also provided the flexibility required to fit around the Passive Plate assemblies. The average resultant mandrel cross-sectional area was 0.259" by 0.747" (see Fig. 3).

The same winding pitch of 77 turns per inch as the halo current loops was used. Due to the high temperature requirement, the same ceramic insulated AWG No. 30 magnet was used.

The average winding length was 40.5" for the Secondary Passive Plate installation and the average winding length was 59" for the Primary Passive Plate installation. The mandrel lengths were longer for the winding process.

The first tests revealed the same design problem with windings shorting; the rework process was identical.

For the eddy current loops, maintaining a critical length was not necessary; therefore, the ceramic mandrel ends were trimmed to achieve a space of 1/8" to 1/4" from the actual fabricated magnet wire winding lengths.

To protect and insulate the ceramic winding, a Nextel one-inch ceramic tape was one-third lapped wrapped around the winding/mandrel assembly; thickness build-up was not critical. All the other fabrication details were identical to the halo current loops.

C. Test Results

The Rogowski Loop test setup (Fig. 2) was used to perform the scale factor measurements.

The average tested scale factor was:

$$V_o = 0.457 \frac{dIp(t)}{dt}$$

where V_o = the loop output voltage in volts

I(t) = eddy current (megamps)

The tested scale factors were approximately 4% lower than the calculated scale factor. The eddy current loops were the first units to be reworked; there probably are some shorted turns in these assemblies. The average resistance of the secondary passive plate loops with approximately 7' of field cable was 69.7 ohms, with an average inductance of 1.6 millihenrys. The average resistance of the primary passive plate loops with approximately 7' of field cable was 96.5 ohms, with an average inductance of 2.1 millihenrys.

D. Installation

In between the passive plate assemblies, there is a 2" vertical space with a partial overlap of the carbon tiles which results in a 1" opening to the plasma. In selected openings on both primary and secondary plates, there is a stainless steel bracket with some Mirnov coils attached to them. The field installation of the eddy current loops used one side of these brackets, and required a second bracket welded on to the opposite side of the plate assemblies for mounting. The loops were held to the brackets by stainless steel straps that clipped on to the brackets. After making the loop snug to the bracket, the other side of the strap was welded to the bracket. The brackets provided the vertical support for the loops; the loops were tied off to various cooling tubes on the top and bottom using 1/16" OD, 1200°F fiberglass sleeving to provide the remaining support. The signal leads were routed to the nearby feedthru connectors.

Due to scheduling demands, only the eddy current Rogowski Loops on the bottom half passive plates were installed at this opening for a total of five loops.

V. FUTURE ROGOWSKI LOOP REQUIREMENTS

Currents in the Center Stack and the passive plate supports were successfully measured with the Rogowski Loops. Any future requirements for Rogowski Loops depend on operational results, budget, and time restrictions but the following are possibilities: (a) install the balance of the eddy current loops, (b) install loops around some portion of the inner and outer divertors. The choices require more investigation and operational data analysis.

Acknowledgements: Many people provided assistance and insight; I would like to thank E. Bush, J. Carson, W. Derry, S. Edwards, G. Gibilisco, K. Gilton, L. Guttadora, T. Holoman, P. Kivler, R. Knoll, G. Rossi, and F. Simmonds.

* Work supported by U. S. D. O. E. Contract DE-AC02-76-CH03073.