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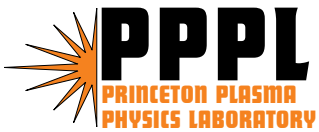
Analysis of NSTX TF
Joint Voltage Measurements

R. Woolley

October 2005

Princeton Plasma Physics Laboratory
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Analysis of NSTX TF Joint Voltage Measurements*

R. Woolley

Princeton Plasma Physics Laboratory,POBox 451, Princeton, NJ08543

Abstract—**This report presents findings of analyses of recorded current and voltage data associated with 72 electrical joints operating at high current and high mechanical stress. The analysis goal was to characterize the mechanical behavior of each joint and thus evaluate its mechanical supports. The joints are part of the toroidal field (TF) magnet system of the National Spherical Torus Experiment (NSTX) pulsed plasma device operating at the Princeton Plasma Physics Laboratory (PPPL). Since there is not sufficient space near the joints for much traditional mechanical instrumentation, small voltage probes were installed on each joint and their voltage monitoring waveforms have been recorded on sampling digitizers during each NSTX "shot".**

Strong mechanical forces arise during pulsed operations, far stronger than the joint conductors could long survive without the restraining assistance of a mechanical support system. A joint's apparent electrical resistance changes dynamically if sufficiently strong net lateral force on the conductors causes a reduction in the joint's area of high pressure contact. Since the electromagnetic forces are well known, this circumstance would arise if the mechanical supports were not working properly. Analyzing the nonlinear relations between pulsed magnetic forces and joint electrical resistances can thus identify and even diagnose mechanically overstressed joints.

The present design of the joints and their supports was operated in two successive run periods, February-July 2004 and April-September 2005. Because of indications from analyzing the first run period's voltage probe data that the mechanical support system's fabrication was flawed, the joints and their mechanical supports were rebuilt before the second run period without changing the design. Analyses of voltage probe data from the second run period indicate improved mechanical support function.
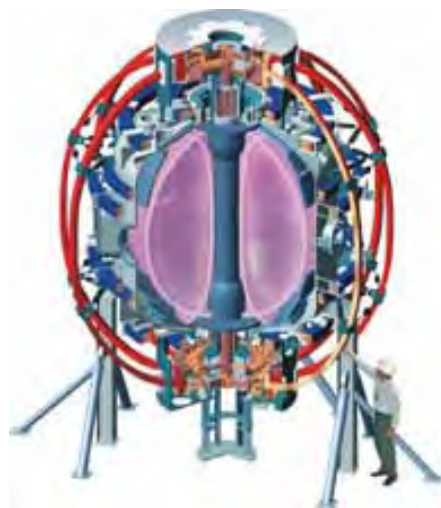
Figure 1.   NSTX Schematic

I.   INTRODUCTION

Low aspect ratio tokamaks such as the NSTX are being researched at PPPL as a plasma confinement scheme with promising attributes for future fusion reactors. The Figure 1 schematic depicts the toroidal plasma surrounding a "center stack" inside a roughly spherical vacuum vessel approximately twelve feet tall. During pulsed operations the plasma conducts a toroidal electrical current (looping around the center stack) of about one million amperes. Ten separate multiturn Poloidal Field (PF) coil winding sets, including the Ohmic Heating (OH) coil which induces the plasma current, conduct toroidal currents parallel to the plasma current.
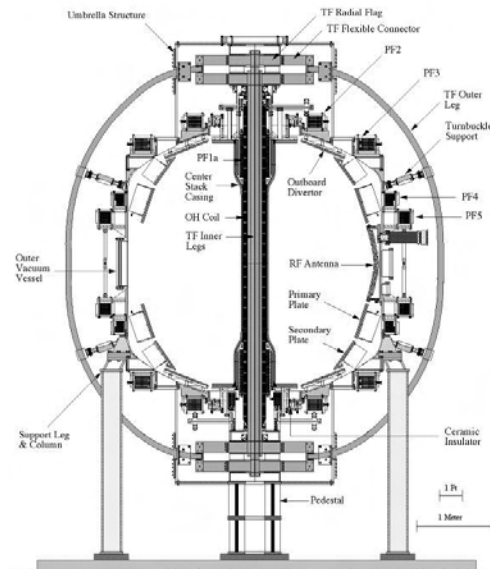

Figure 2.   NSTX Cross section

The Figure 2 cross section view of the NSTX depicts features relevant to this analysis. The 36 series-connected Toroidal Field (TF) coil turns are mechanically divided into a cylindrical 8 inch diameter 18 foot tall inner-leg subassembly located at the middle of the centerstack, and twelve 3-turn outer-legs returning the TF current between top to bottom outside the vacuum vessel in symmetrical poloidal planes. The TF inner-leg, threaded inside the OH solenoid winding, has a 12 turn inner layer and a 24 turn outer layer. At four elevations, the outer-legs are electrically connected via "TF Flexible Connectors" to rigid "TF Radial Flag" assemblies which in turn are bolted in tiers against the two layers of inner-leg turns, thus forming the 72 TF electrical joints which are the subject of this analysis.

Figure 3 shows one of the radial flags in isolation without any of its mechanical support features.
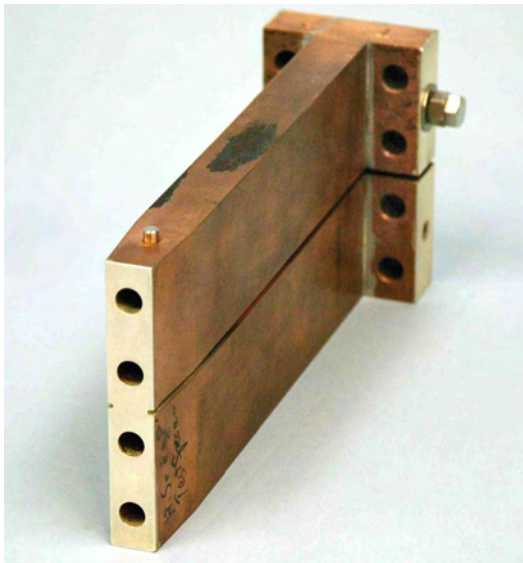
Figure 3.   TF Radial Flag

A TF radial flag is a 5 inch tall copper bar about 12 inches long, with its 1 inch width tapering down to 0.78 inches at the TF joint interface, in the foreground of Figure 3. The outer end of the radial flag has a "tee" for bolting to the TF flexible connectors. The inner end forming the TF joint is silvered to improve electrical conductivity. The four holes provide access for long bolts, screwed into threaded inserts in the associated inner-leg TF turn and pretensioned to 5,000 pounds each. The horizontal grooves visible in Figure 3 accommodate the voltage monitoring probes and their cables (not shown). The probes are each insulated coaxial assemblies with a spring-loaded center conductor to press against the associated TF turn and a press-fit electrical contact with the flag a short "setback" distance (about 0.2 inches) back from the joint face. Although both sides of each flag have voltage probes installed, only the "B" probes (on the right sides) have always been connected to digitizers during each shot since February 2004. A small and variable subset of the "A" probes (on the left sides) have also been connected to spare digitizer channels.

Joint voltage signals are sensitive to noise and interference. Probe voltage differences are in the millivolt range while the common mode voltage is in the kilovolt range. Since the ac common mode rejection of the instrumentation amplifiers is not perfect, the result is that differentiated TF circuit voltage transients couple to the recorded signals in addition to the intended joint voltage drops. The unwanted signal components include thyristor power supply noise as well as spikes at breakpoints in the slope of the TF current waveform. Since each TF joint voltage signal is sampled at a 2000/second rate, thyristor ac common mode contribution to the signal is easily recognized (see Figure 4a), and is well removed by a 15 millisecond FWHM triangular FIR filter without severely distorting real signal dynamics (see Figure 4b). However, a voltage spike remains from the power supply turn-on transient, even though it is not part of the true joint voltage drop.

In addition, changes in the TF current level cause decaying eddy current patterns to circulate through different parts of a joint, transiently affecting voltage measurements at probe locations. For instance, this can cause a brief measured joint voltage reversal at the end of a unidirectional current pulse, as appears in Figures 4. Because eddy current patterns change nonlinearly with TF joint conditions, it is not practical to model and cancel them out as would be possible for purely inductive effects. Sophisticated data mining methods [2] have been used, but focusing on stationary TF current conditions avoids confusing these effects with true apparent resistance variations.
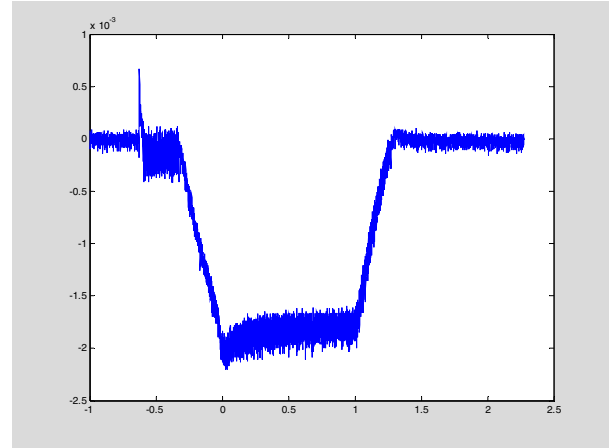

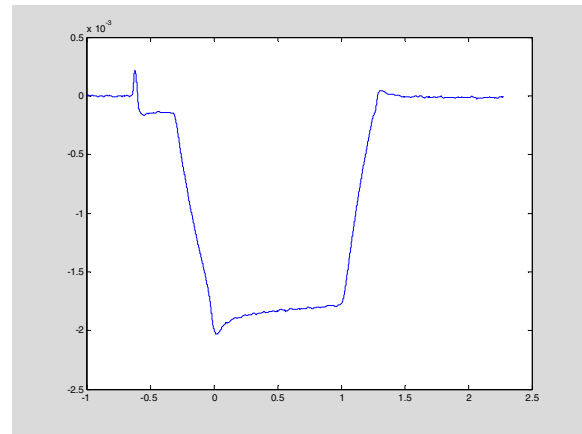Figure 4a: Raw TF Joint Voltage Measurement Data

Figure 4b: Filtered Raw TF Joint Voltage Measurement Data

In order to interpret the voltage signals a multiphysics ANSYS model of a TF joint was created without any support structure, as depicted in Figure 5.
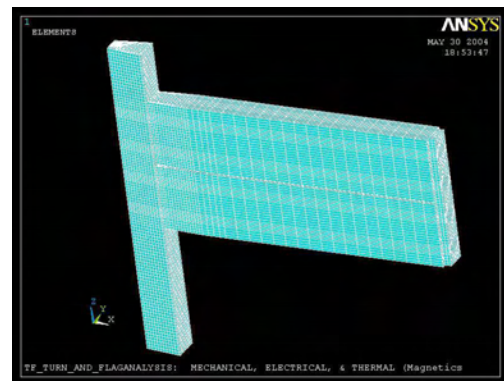

Figure 5: ANSYS Multiphysics Model of TF Joint

A simple argument from statics[1] proves joint pressure distribution is determined by torque about the joint's center and the fixed bolt tension. Figures 6a-6e show ANSYS calculated joint pressure distributions with "in-plane" (IP) only torques at 10 kilo-inch-pound increments. Although the maximum expected joint torque at full design TF (0.6 Tesla) was 18 kip, Figure 6 also shows the joint's pressure response at higher IP torques up to 40 kip. This was done because electromagnetic forces actually would apply 70 kip to the TF Flag, and the mechanical support system was expected to absorb 75% of it, thus protecting the joint.

The plots show progressive "lift-off" of the high field side of the joint and the increase of contact pressure on the low field side to intense levels for OFHC copper. (Note yellow signifies 200-350 MPa and red is above 350 MPa).
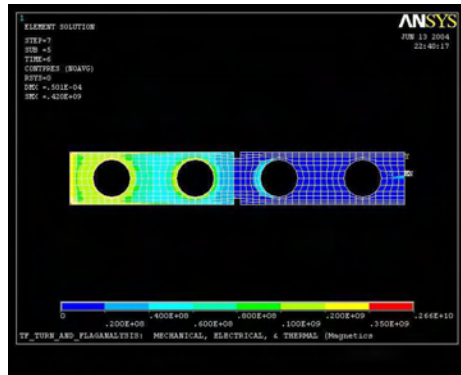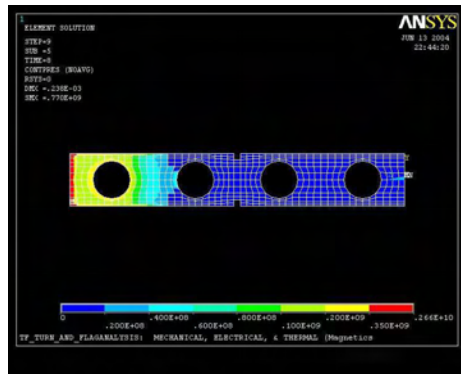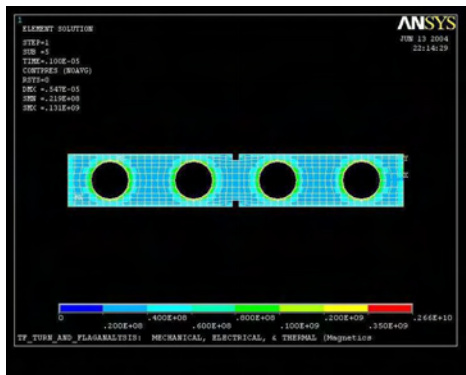

Figure 6a: IP=0 kip

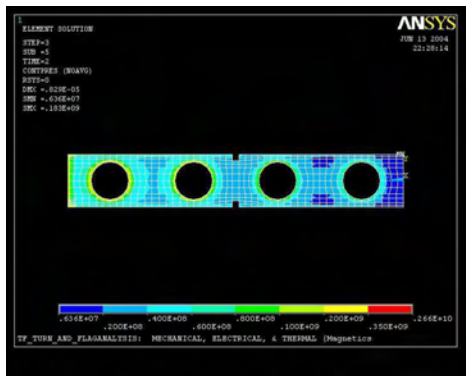Figure 6b: IP=10 kip

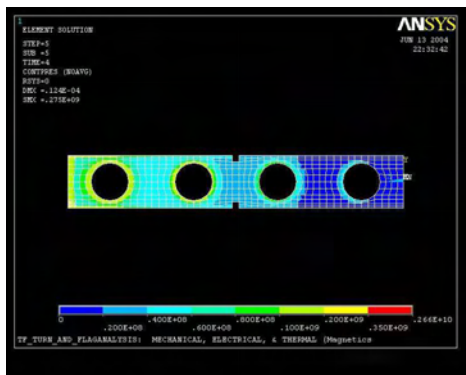Figure 6c: IP=20 kip

Figure 6d: IP=30 kip

Figure 6e: IP=40 kip

TF joints cannot survive the full 70 kip IP torque applied to the TF Flag at full TF without help from a mechanical support structure. The designed structural support relies on epoxy-glass potting compound injected into "flag-boxes' after joint assembly. These boxes are bolted to hub disks forming beams opposing balanced IP torques. Out-Of-Plane (OOP) torques are opposed by sliding "spline" structure connecting upper and lower hub disks through the vacuum vessel.

The ANSYS model was given the conductivity vs pressure curve of Figure 7, which had been obtained from bench tests on a silvered joint.
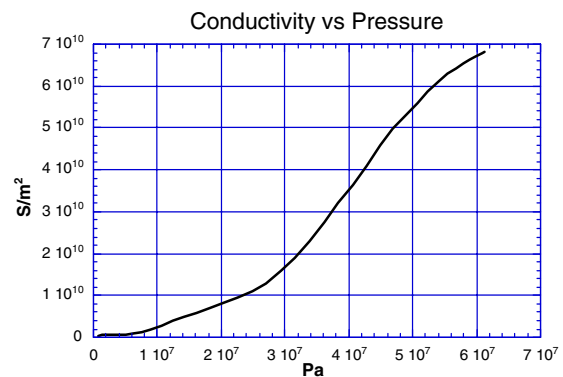

Figure 7: Electrical Resistance Model of Contact Surface

ANSYS then solved for voltage at probe locations w/ fixed current. The resulting 1D relation for TF-only shots appears in Figure 8 (for a setback distance of 0.2 inches).
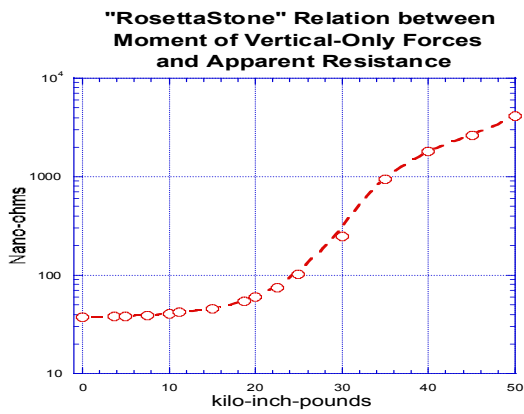
Figure 8: 1D "RosettaStone" Relation from ANSYS

The complete 2D "RosettaStone" relation between apparent resistance and the IP and OOP torque components was then obtained via an extensive series of ANSYS runs. It uses two 2D numerical functions contour-plotted in Figures 9a and 9b.

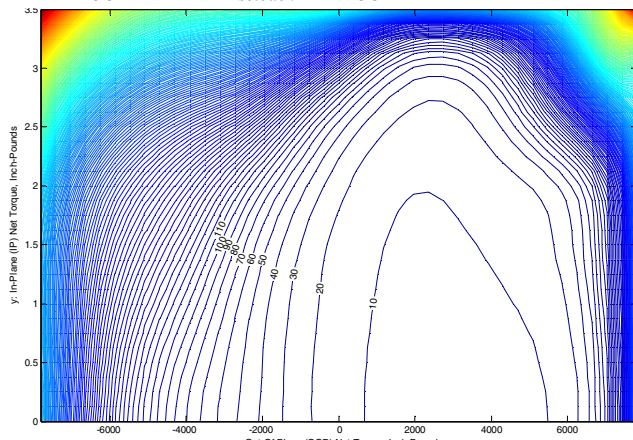$$R = f_1(T_{OOP}, T_{IP}) + c_{setback} f_2(T_{OOP}, T_{IP}) \qquad (1)$$

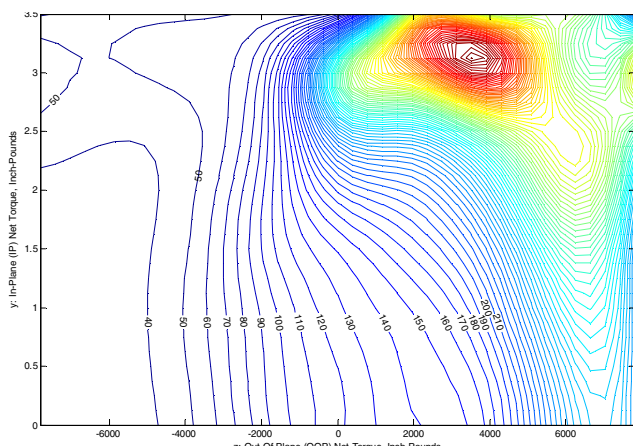Figure 9a: Surface Contact "RosettaStone" Function f_1.

Figure 9b: Setback "RosettaStone" Function f_2

During CY2004, TF joint voltage probes showed large variations in apparent resistance. For example, during the 0.45 Tesla TF-only shot 113125 the apparent resistance of joint 22-

22 varied from 30 to 127 Nano-ohms. The RossettaStone relation translates this variation into about 27 kip of IP torque. Since the max EM IP torque was less than 40,000 inch-lb, that means 67% of it was reaching the joint instead of the 25% expected for the designed support structure, thus revealing inadequacy of the as-built system. After this structural interpretation was understood, NSTX operating levels were reduced for the remainder of the CY2004 run.

The support system was inspected and disassembled after the CY2004 run was finished. The main problem found was that epoxy/glass potting had left many large voids. Process and materials changes were devised to improve quality and the system was rebuilt before the CY2005 run.

Figures 10 compare a CY2005 0.45 Tesla TF-only shot response (green) to CY2004 (red). The Rosetta relation indicates the IP torque on the joint has been reduced to under 10,000 inch-lb, matching design expectations.
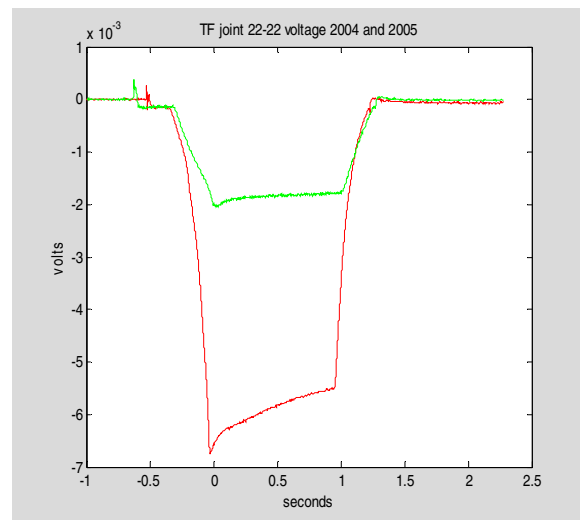

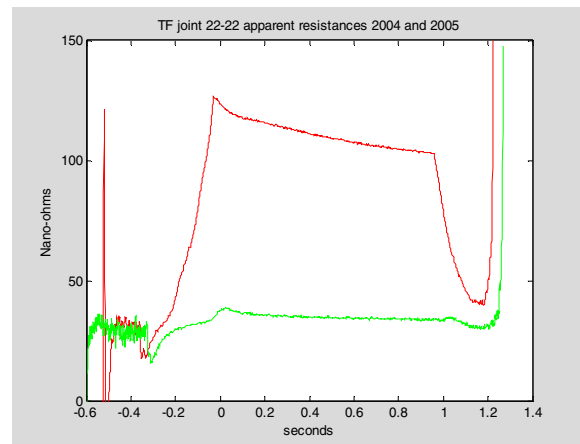Figure 10a: TF-Only Voltage Response CY2004 & CY2005

Figure 10b: TF-Only Apparent Resistance CY2004 & CY2005

Figures 11a and 11b show, for each CY2004&CY2005 shot, the maximum observed resistance (red) and the zero-torque SOP (blue) resistance. Note that a mechanically ideal joint would have constant apparent resistance, and that these

plots show that situation is approached much more closely during CY2005 than during CY2004.
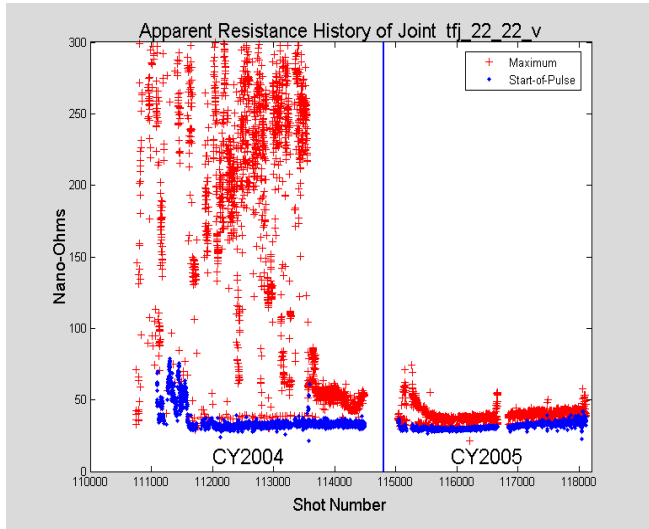

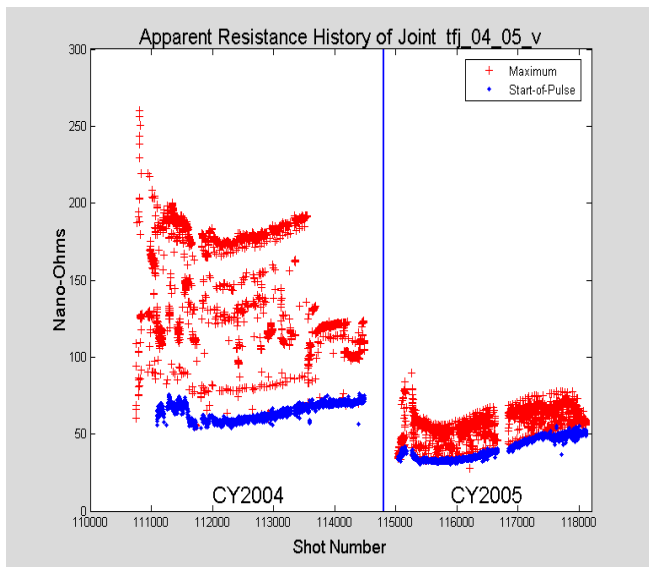Figure 11a: TF Joint 22-22 History of Apparent Resistance Variability

Figure 11b: TF Joint 04-05 History of Apparent Resistance Variability

Although the CY2005 performance is clearly much improved, the voltage data behavior still contains two unresolved mysteries. First, many of the joints show unexplained increasing trends of apparent resistance during the run periods, e.g., as appear in Figures 11. Additional ANSYS runs to investigate loosening as a possible explanation concluded that bolt tensions would need to reduce by about 40% to explain the trends. Such a large loosening does not seem likely. Other suggested mechanisms such as degradation of the silvered surfaces are obscure.

Second, it was a surprise that for the CY2005 data, although the OH system does have an appreciable effect on apparent resistance, PF coil currents have no appreciable effect. Figure 12a shows the coil currents for a combined field TF/OH test shot, and Figure 12b shows a TF joint voltage response to it and to other identical TF/OH test shots.
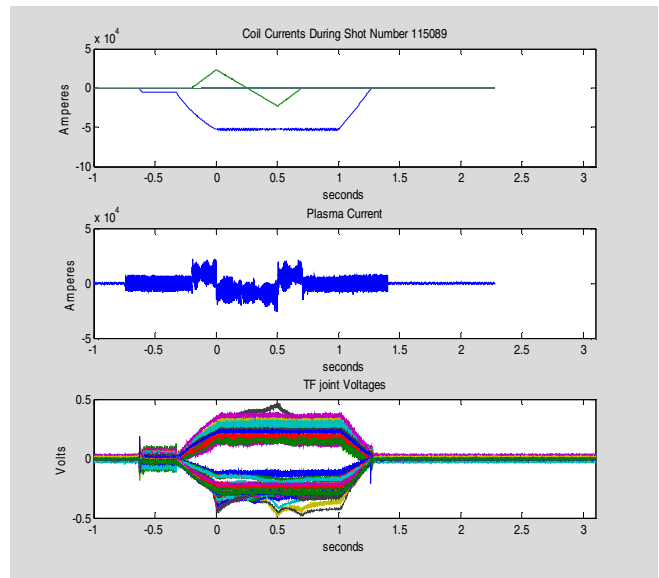

Figure 12a: A TF/OH Test Shot
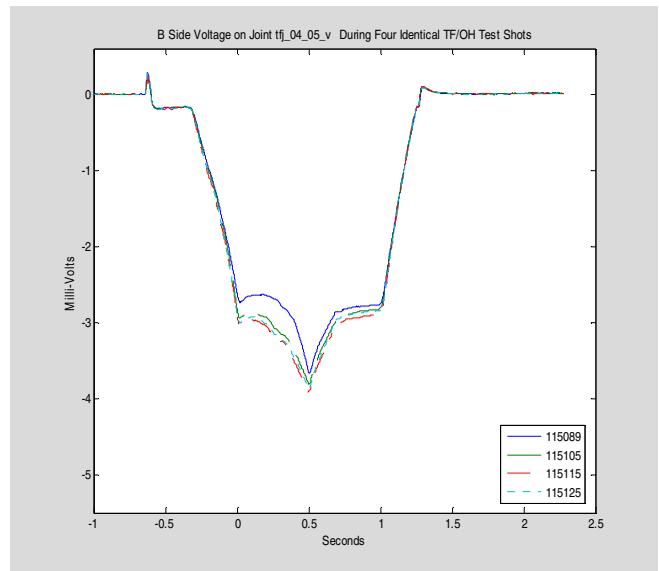
Figure 12b: TF Joint Voltage Response to TF/OH Test Shots

Figures 13 show the CY2005 mean apparent resistances at 0.45 Tesla toroidal field strength for each of the 48 high field "outer" TF joints, at OH currents of -24, 0, and +24 kiloamperes. Some joint resistances increase with OH while others decrease. Many show a quadratic dependence, increasing with either OH polarity.

Especially dramatic is the fact that calculated EM torques per ampere on TF flags are more than 3 times as strong from the PF2 coils than from the OH. Thus, the EM torques on TF flags at 10 kA PF2 current exceeds OH torques on the flags at 24 kA. However, Figures 14 show the absence of any appreciable PF2 effect on apparent resistance.

Figure 13a: Lower Outer TF Joint Apparent Resistances Vs. OH

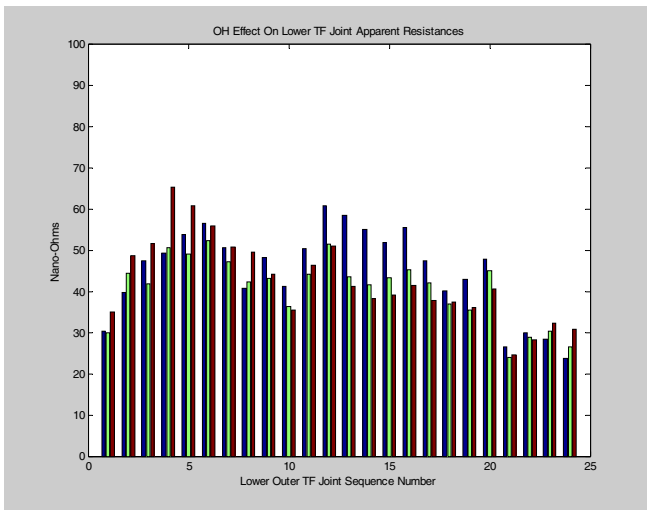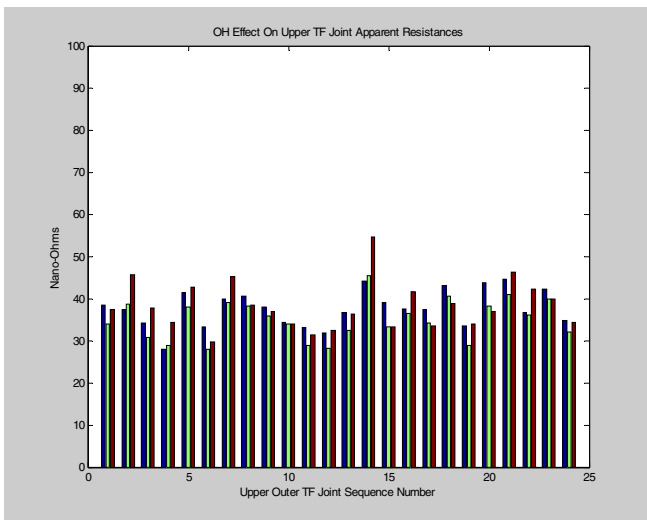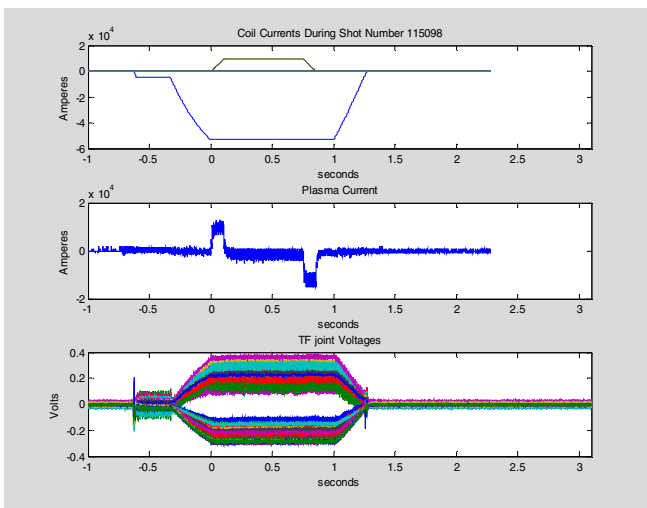Figure 13b: Upper Outer TF Joint Apparent Resistances Vs. OH
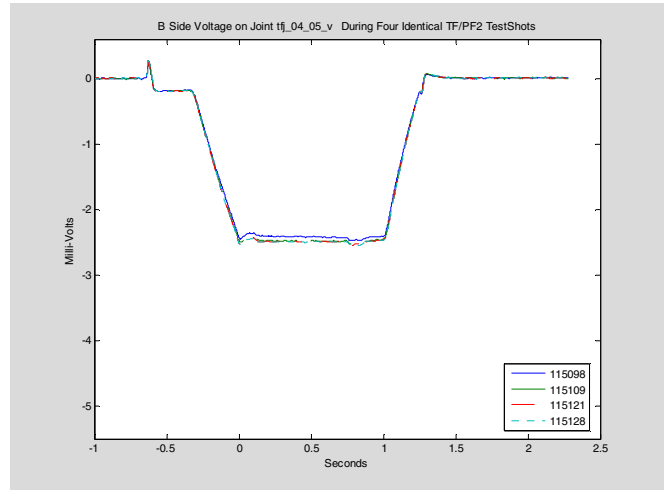

Figrue 14a: A TF/PF2 Test Shot

Figure 14b: TF Joint Voltage Response to TF/PF2 Test Shots

A hypothesis advanced to explain this is that the centerstack bundle of TF turns may be less stiff than anticipated. Then electromagnetic torques developed in the TF flags would not be resisted through the joint. If also individual centerstack turns responded to the OH fringing fields by rotating slightly with respect to each other, that would apply OOP torques to the joints. Since there are no PF fringing fields there, that would explain the unexpected ratio of PF to OH effects.

MATLAB has been used extensively in the analyses of the TF joint voltage measurement data. The MDS data acquisition system software used for NSTX has a convenient existing pre-programmed interface with MATLAB which simplified transfer of the 44 gigabytes of data measured during the two calendar years. The extensive existing inventory of MATLAB preprogrammed functions have been used for investigatory statistical analyses, filtering, simple and nonlinear regressions, PCA analyses [3], and graphics.

CONCLUSION

Voltage probes monitoring bolted joints, combined with ANSYS models for interpretation, were able to find structural deficiencies early and thus avoid failure during CY2004. The same probes in CY2005 show that apparent resistances, and thus the joints, are far more stable. Behaviors not yet understood include the increasing trend of apparent resistance and the unexpected responses to PF and OH.

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[2]   V. Cherkassky, F. Muller, Learning From Data, JohnWiley& Sons,1998

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