NSTX TF JOINT RE-DESIGN

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and the NSTX Team

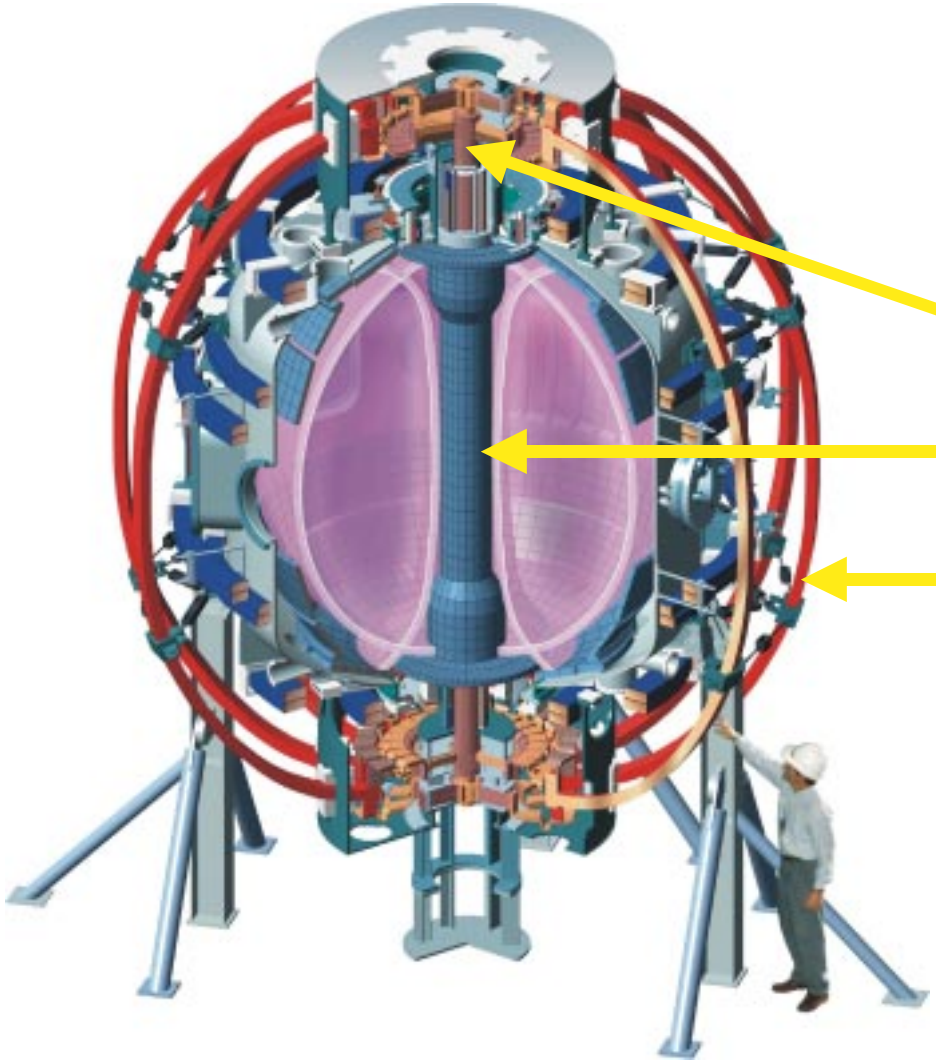
20th IEEE/NPSS Symposium on Fusion Engineering

October 14-17, 2003

Topics

- TF Coil Description
- Failure of Original Assembly
- Forces, Thermal Effects, Load Paths
- Contact Resistance Considerations
- Features of New Design
- Status of Recovery Effort

TF COIL DESCRIPTION



- 36 Turn Copper Coil, Water Cooled
- $B_t \leq 6kG$ at $R_0=0.854m$
- $I_{tf} \leq 71.2kA/turn$

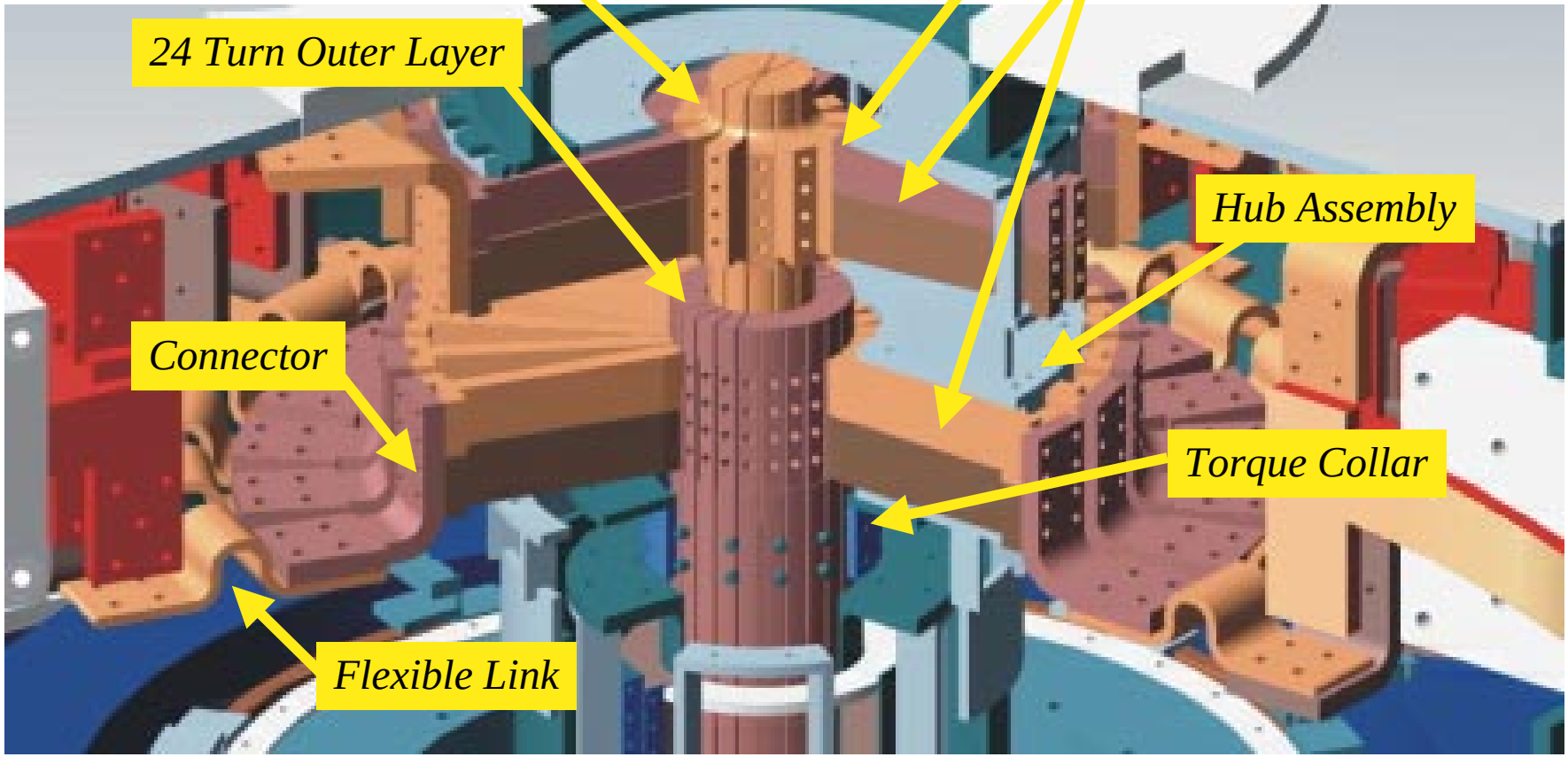
TF Inner Leg Assembly

Demountable Center Stack

TF Outer Leg

Note: Original design shown

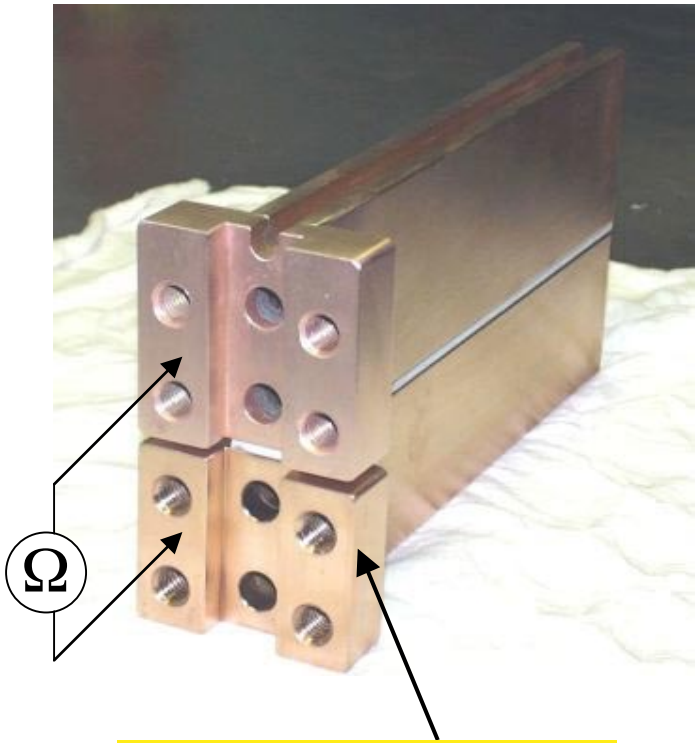
ORIGINAL TF JOINT ELEMENTS



Note: Original Design Shown

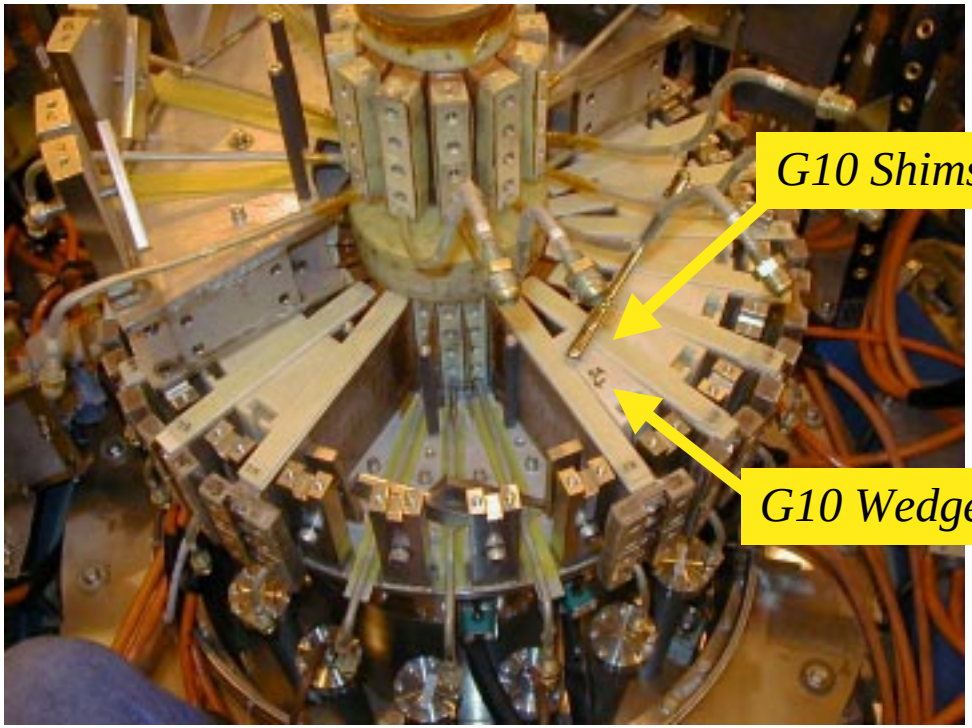
FLAGS, SHIMS, WEDGES

Original Split Flag



Split flag to facilitate joint resistance measurement

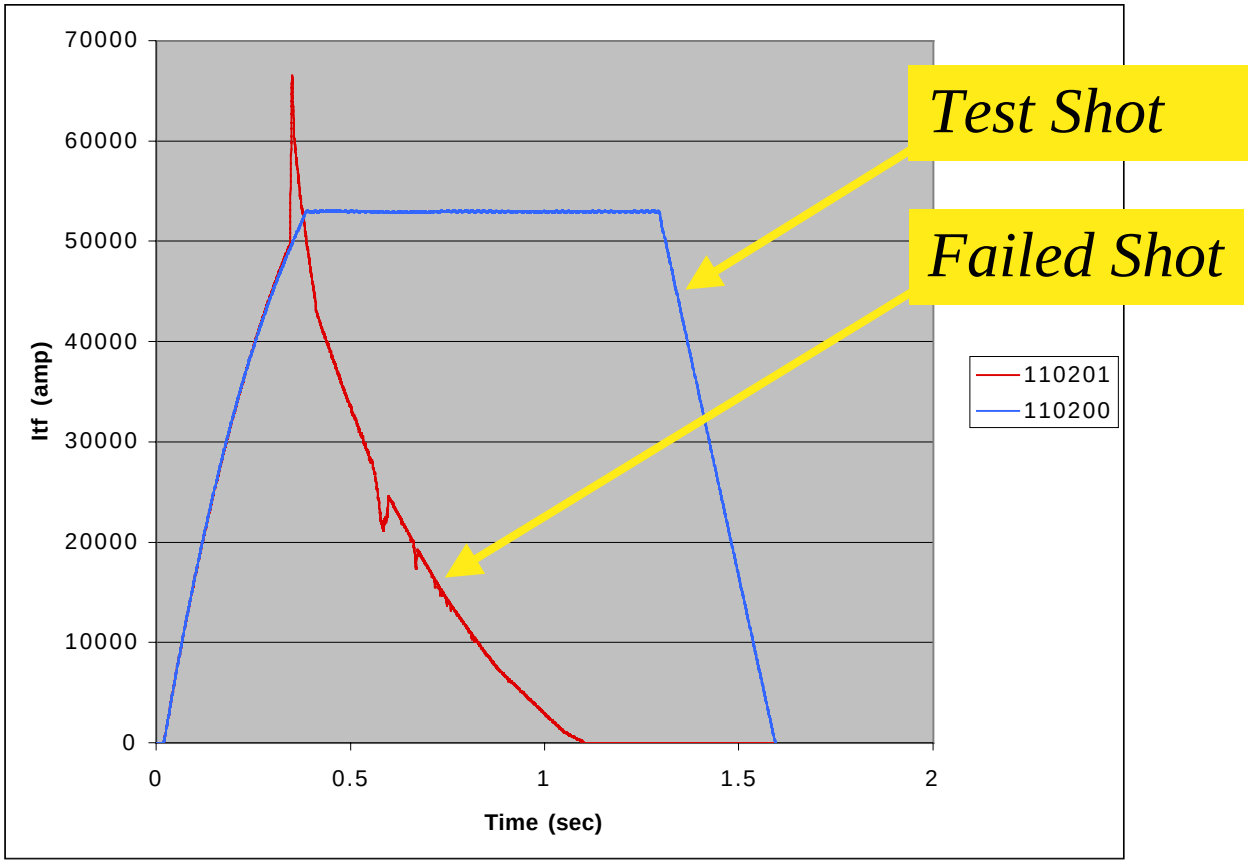
Original Wedges and Shims



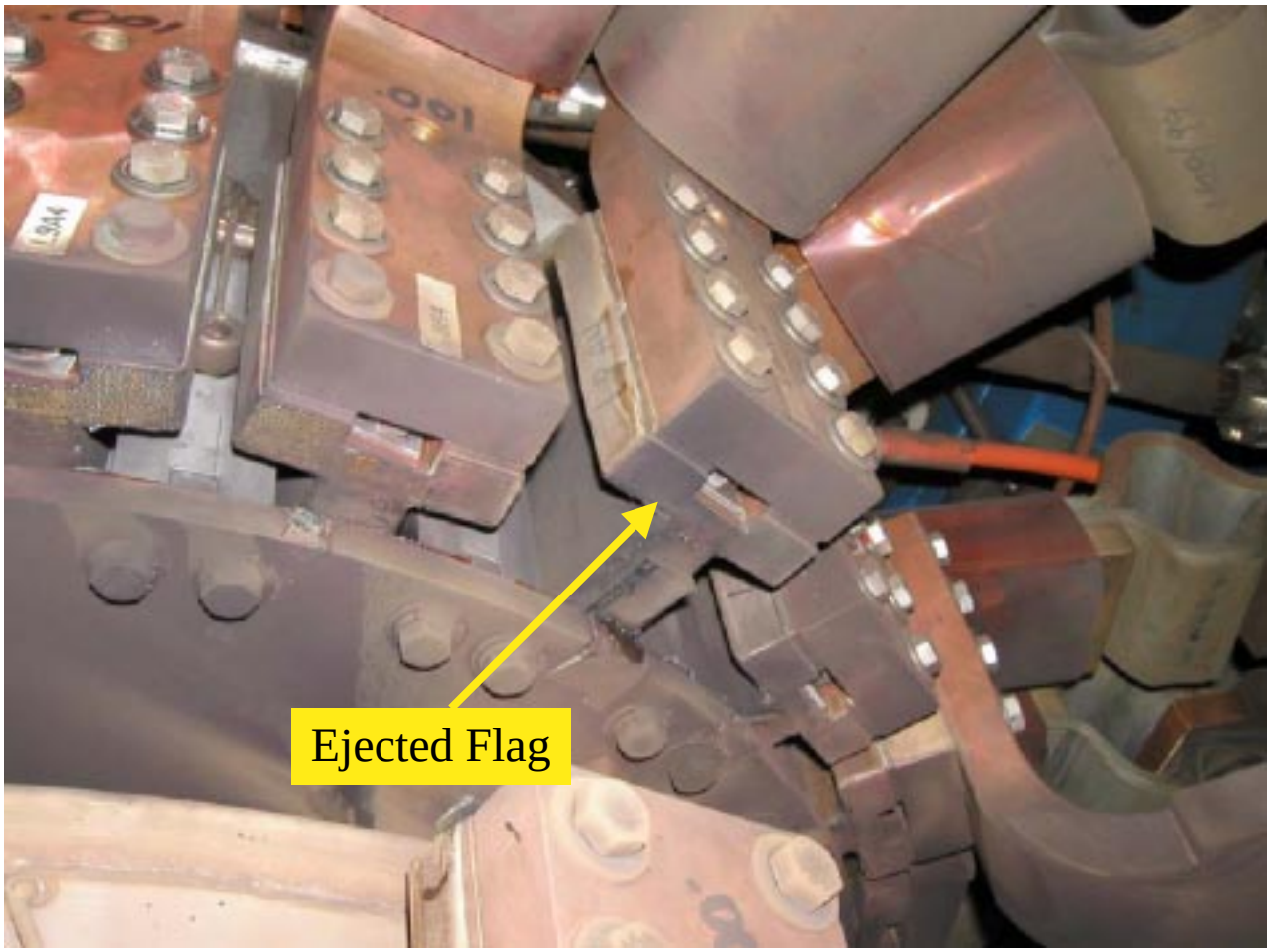
Inadequate Communication of Loads from Flags to Hub

Note: Original Design Shown

February 14, 2003: Following our morning “test shots”, the first plasma attempt of the day resulted in a loud bang (heard on the control room audio monitors) accompanied by a plume of smoke (visible on the control room video monitors).



Initial inspection revealed that one of the TF “flags” on the bottom end of the machine was displaced radially by about 1 inch

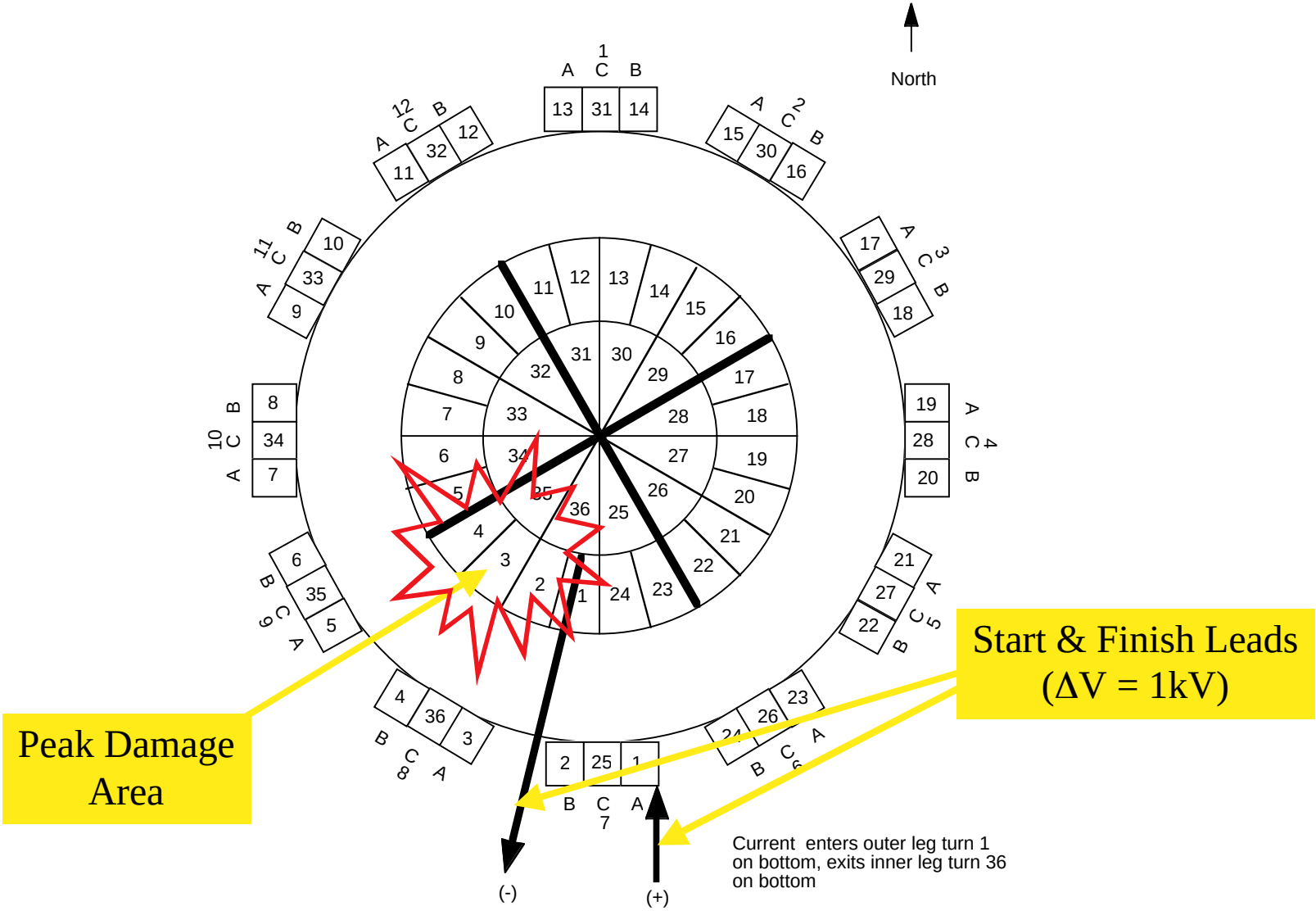


Subsequent inspection revealed the extent of the damage

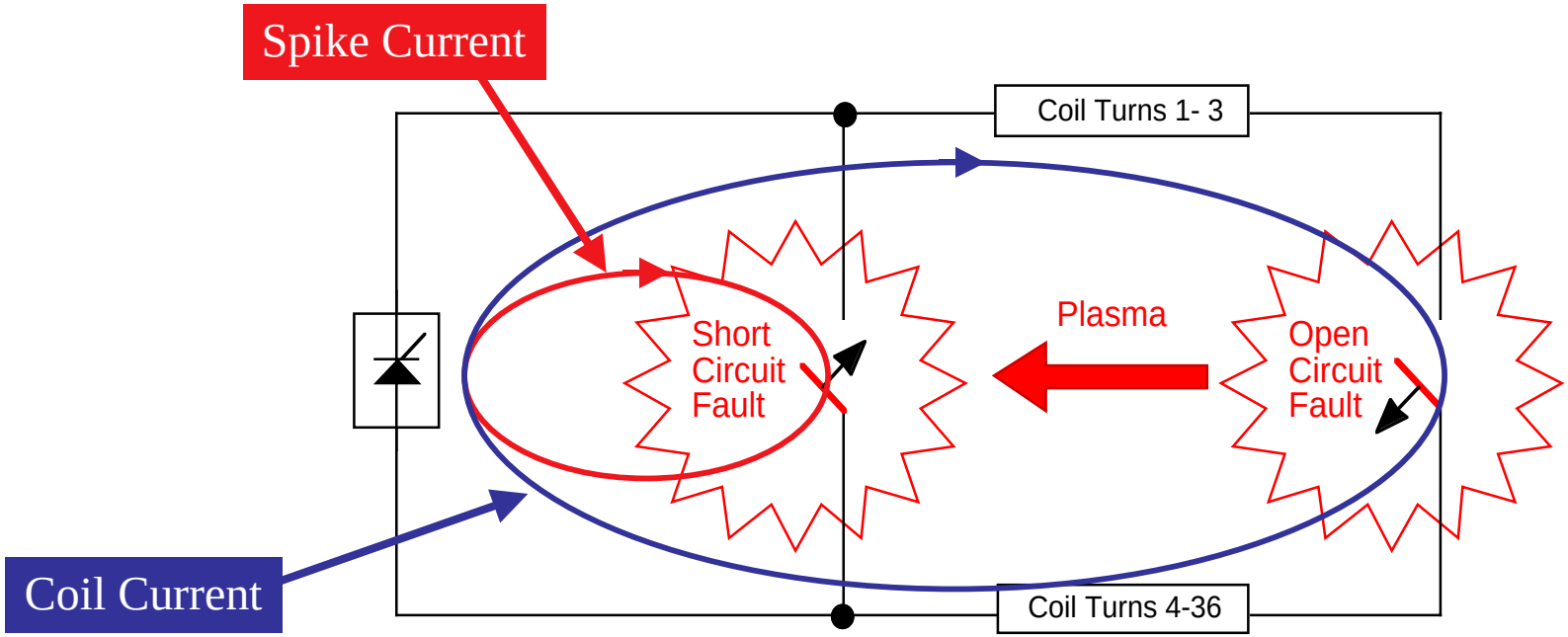
Peak Damage Region

Mating Flags

PEAK DAMAGE AREA

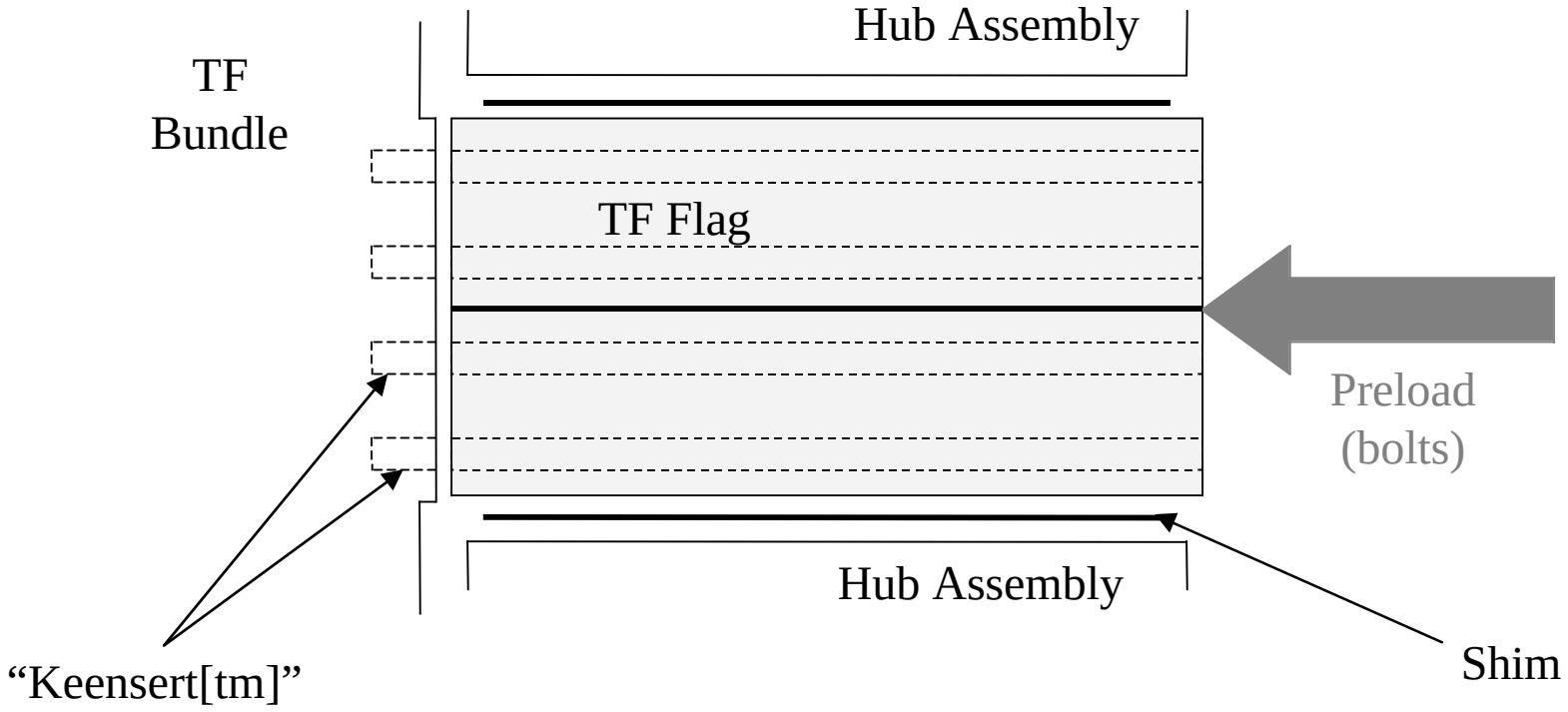


FAULT SCENARIO

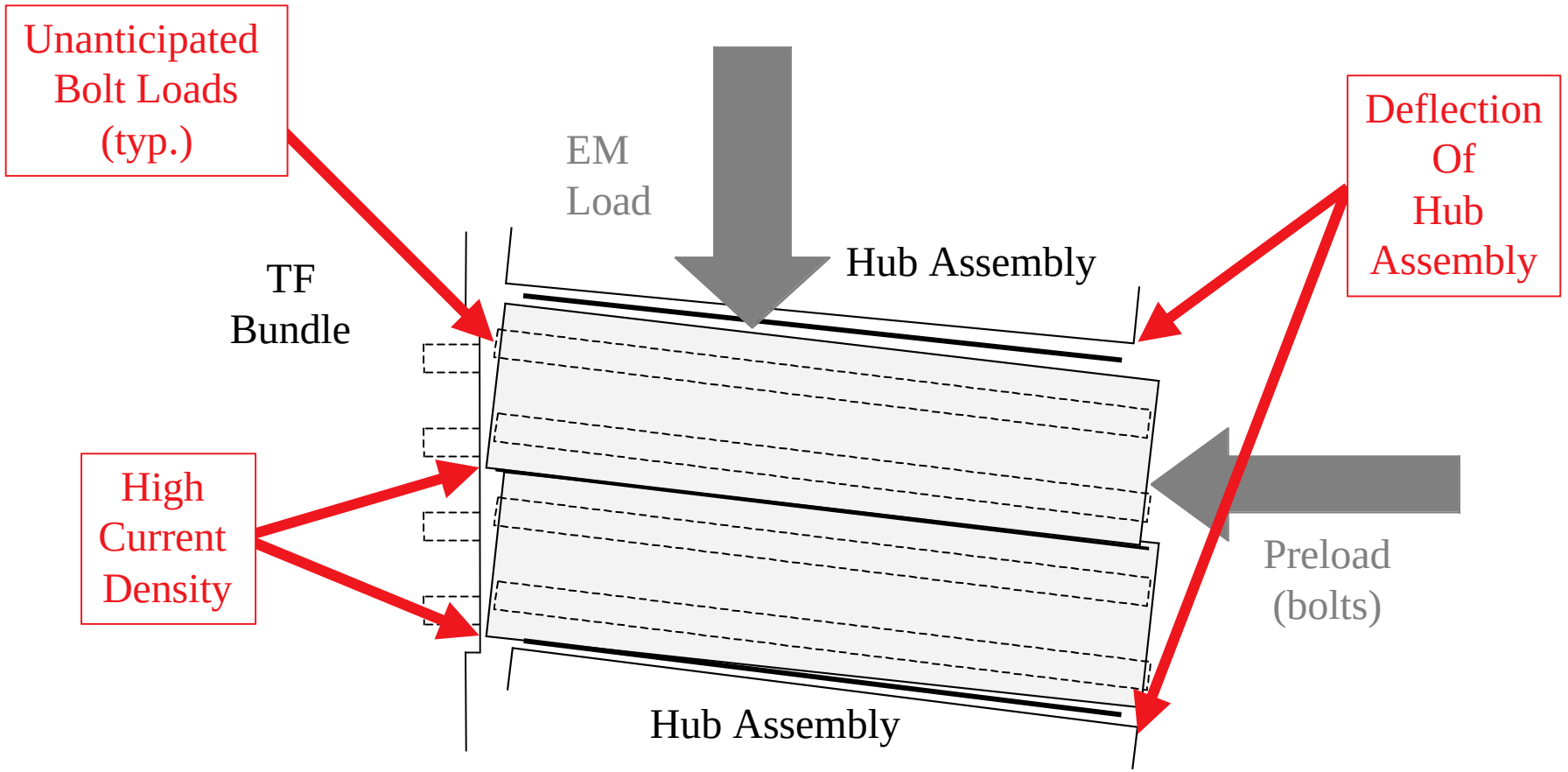


- An open circuit fault at flag joint
- Short circuit fault across coil terminals
- Spike of fault current from the power supply through short circuit
- Power supply tripped, current spike decay
- L/R decay of the coil current
- The energy dissipated in the arc was of order 1.4MJ.

FAILURE OF JOINT

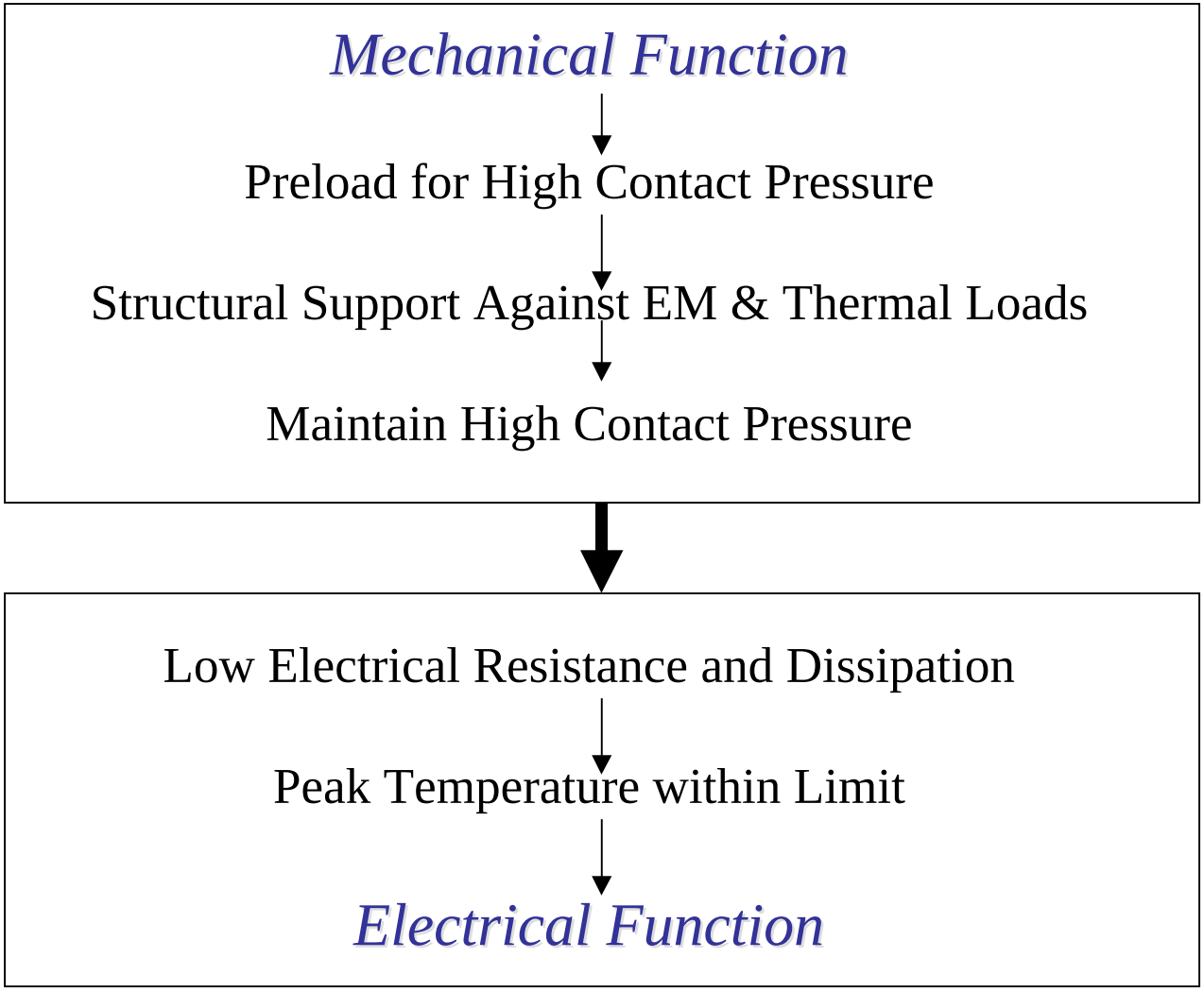


FAILURE OF JOINT

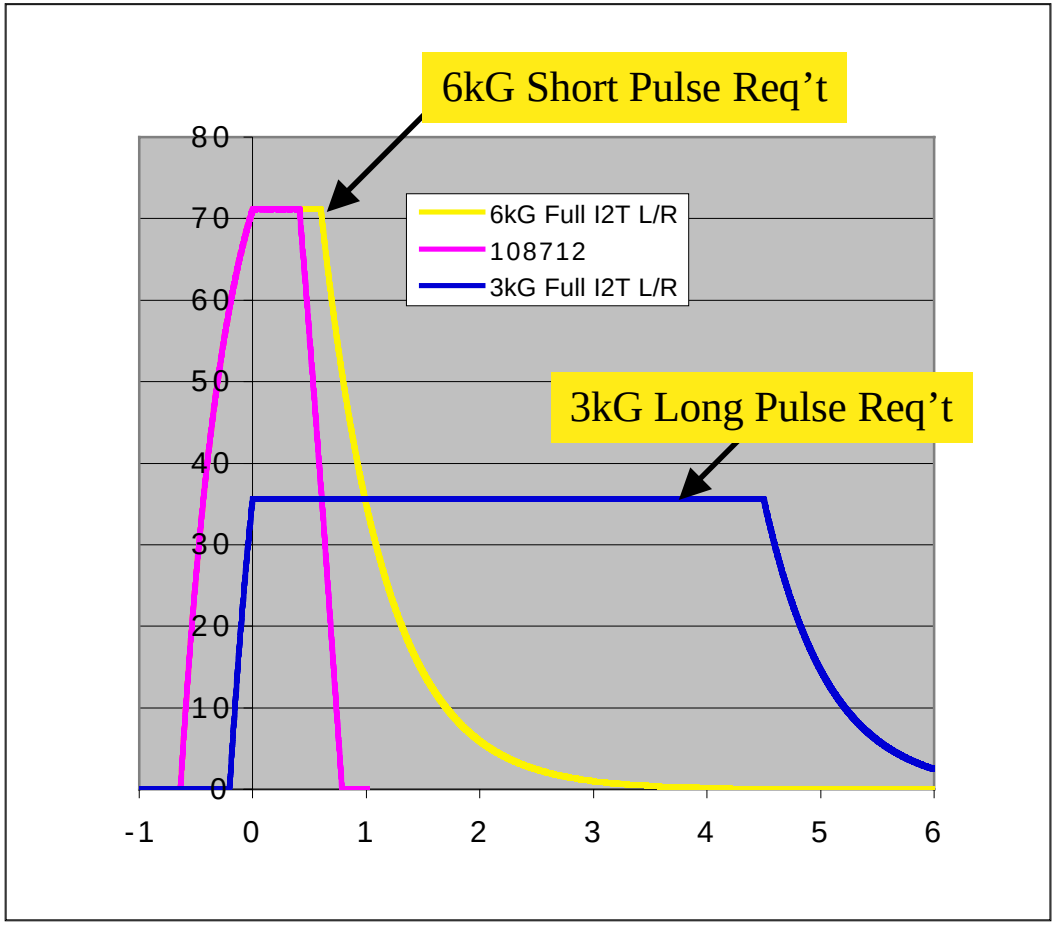


Lack of Hub Stiffness and Shortcomings of Shimming Scheme Led to Cyclic Overload of Fasteners and Eventual Failure

FUNCTIONS OF JOINT



CURRENT WAVEFORMS

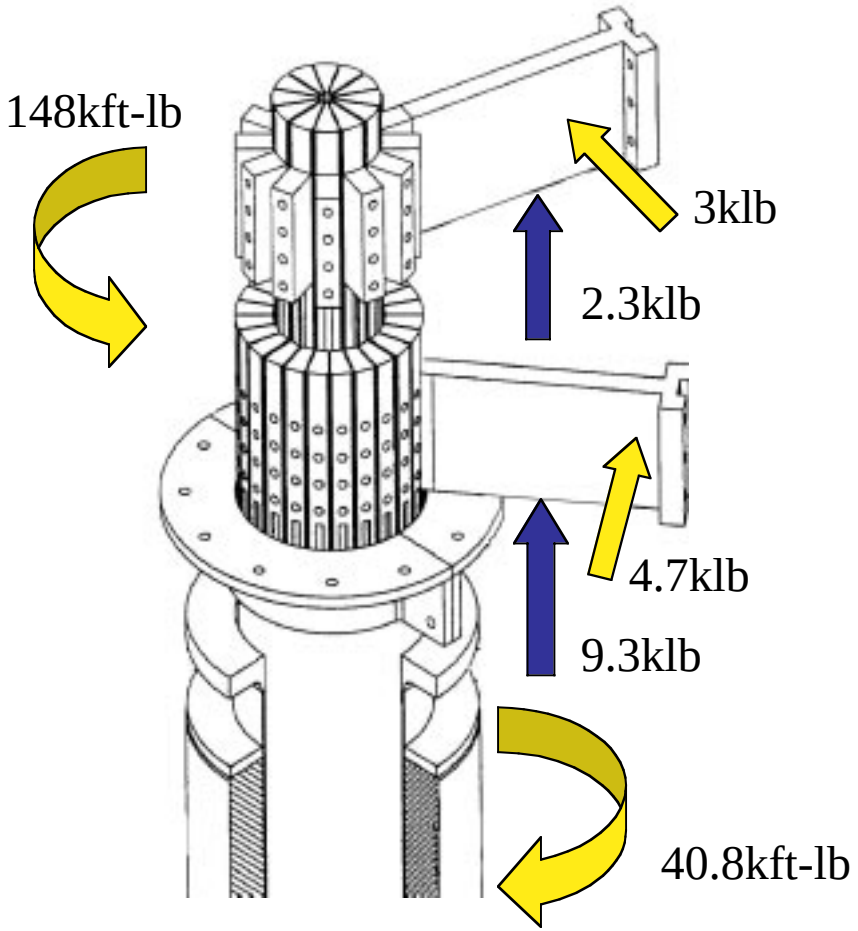


- Design basis $\int I^2T = 6.5 \times 10^9$ A^2-s which causes adiabatic ΔT of 80°C in Cu

- 6kG pulse is most critical for joint since forces are maximum and time for heat diffusion is minimum

- NSTX Research Plan requires only 5% of pulses at 6kG, remainder primarily at 3 and 4.5kG

EM FORCES

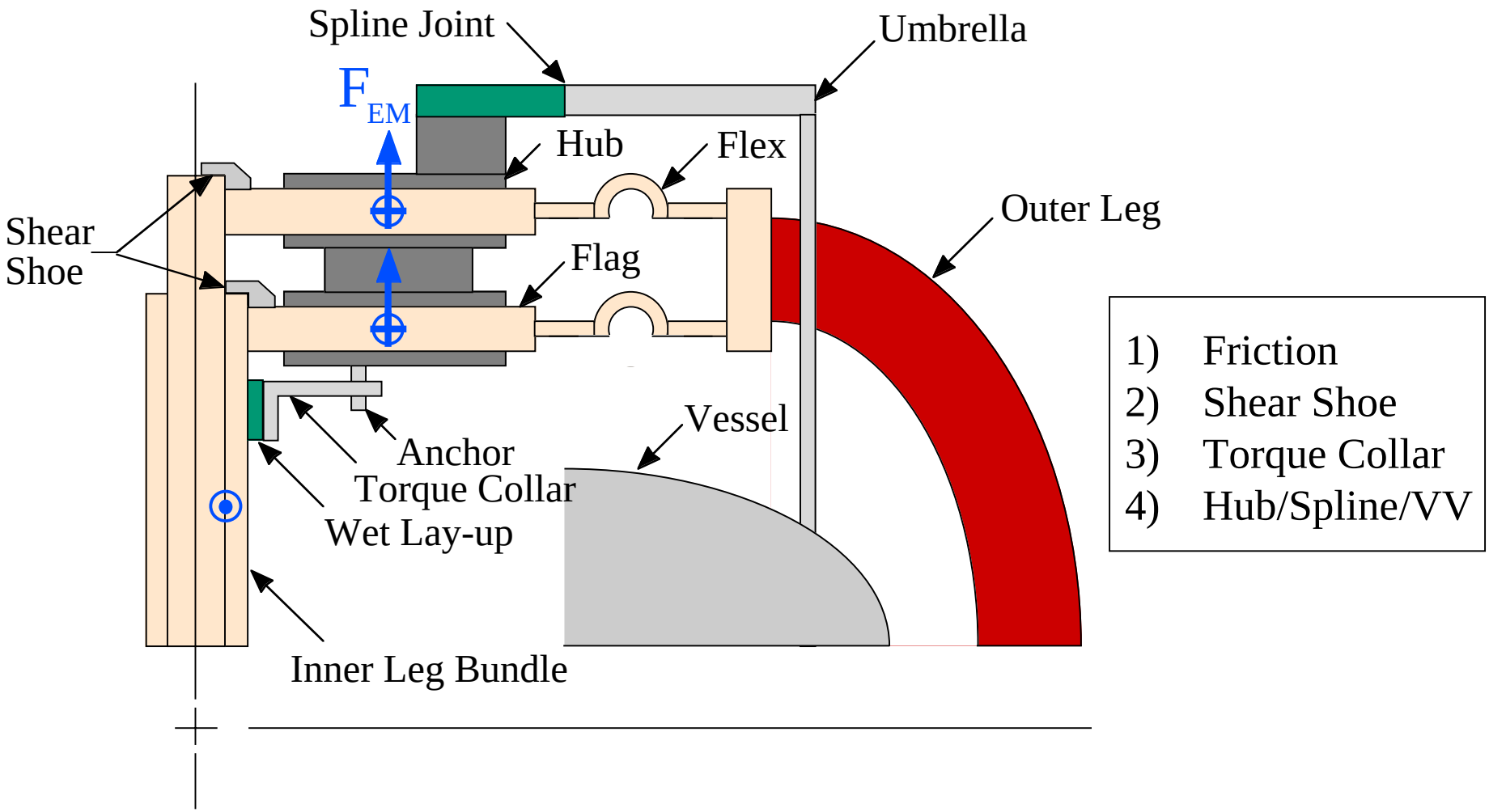


- In-Plane
  - -vertical load and moment due to magnetic pressure from self-field
- Out-of-Plane
  - -lateral due to $I_{tf}xB_{z(oh\&pf)}$
  - -torsional due to $I_{tf}xB_{r(oh\&pf)}$

Notes:

1) *All coils assumed at full current, worst case polarity (conservative)*
2) *Forces equal and opposite on two ends of bundle*

LOAD PATHS


Spline Joint
Umbrella
F_{EM}
Hub
Flex
Outer Leg
Shear
Shoe
Flag
Vessel
Anchor
Torque Collar
Wet Lay-up
Inner Leg Bundle
1) Friction
2) Shear Shoe
3) Torque Collar
4) Hub/Spline/VV

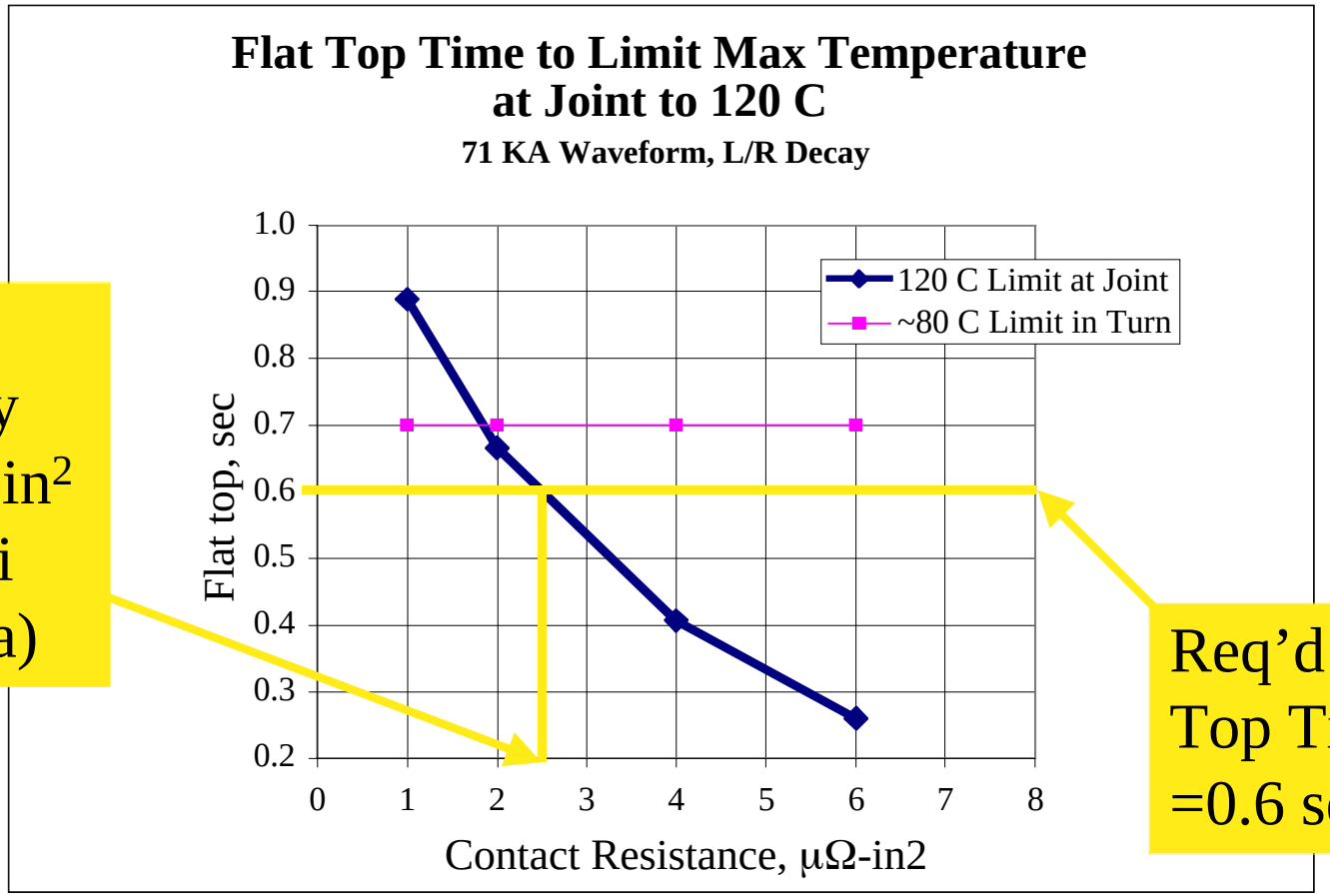
THERMAL EFFECTS

• Vertical length of inner leg bundle from bottom to top increases by up to 0.35” (~ 9mm) during a pulse

• Radius of inner leg bundle increases bundle increases by approximately 0.006” (0.15mm) during a pulse

• Flag heats modestly during pulse ($\Delta T \approx 5^{o}C$) but can ratchet to $\Delta T \leq 25^{o}C$ at rated duty cycle (conservative), $\Delta r \approx 0.005$” (0.1mm) in length

CONTACT RESISTANCE

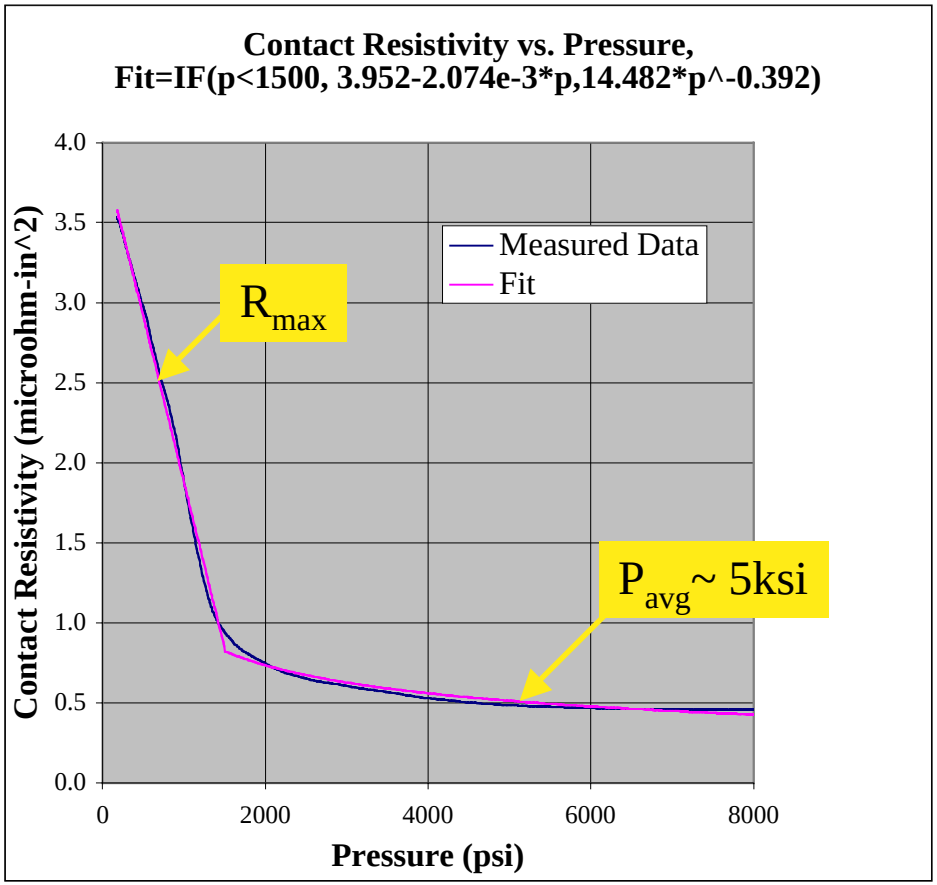


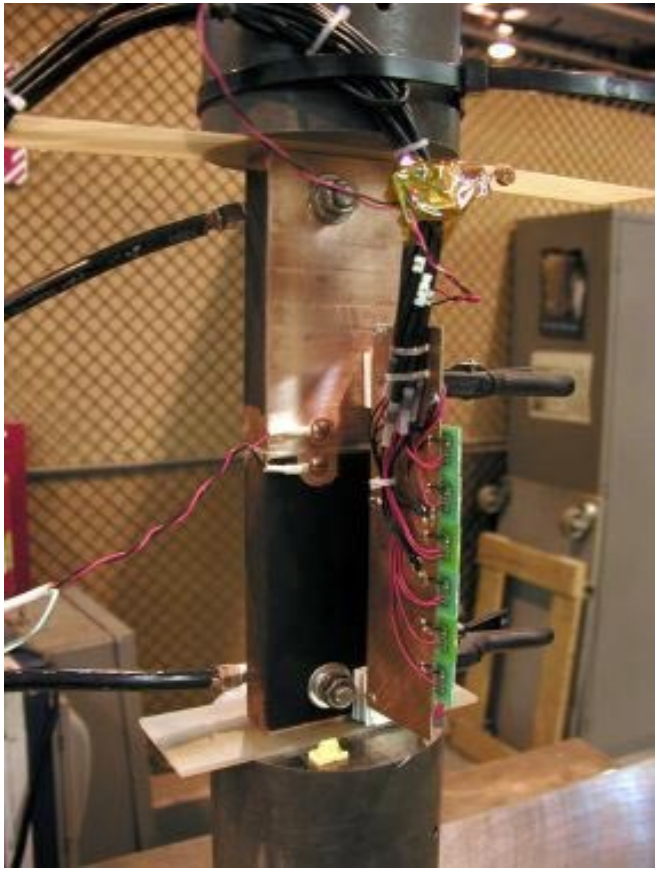
Tolerable Resistivity ≈ 2.5μΩ-in² (700psi ~ 5 MPa)

Req'd Flat Top Time =0.6 sec

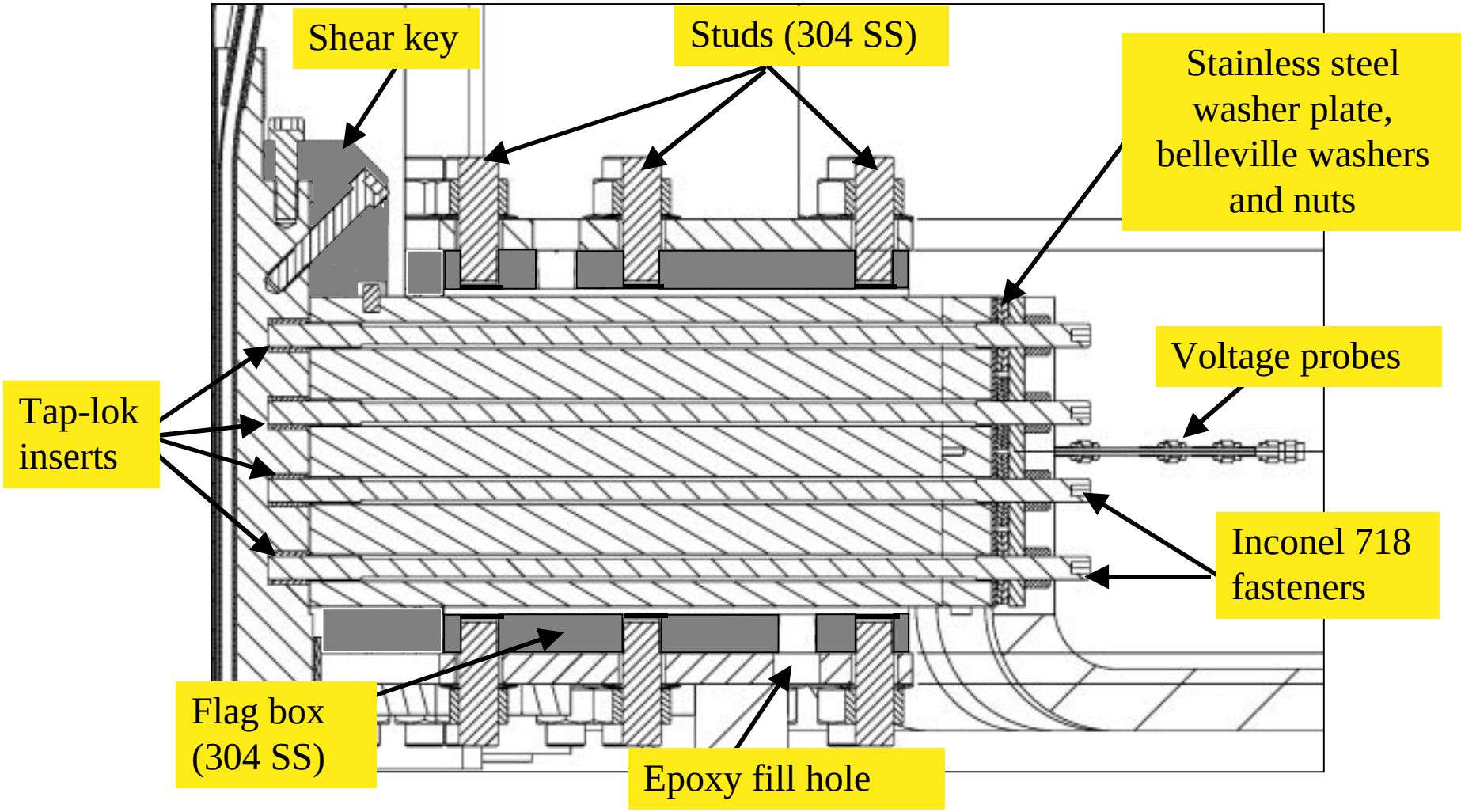
Note: assuming constant resistivity along joint

CONTACT PRESSURE & RESISTANCE

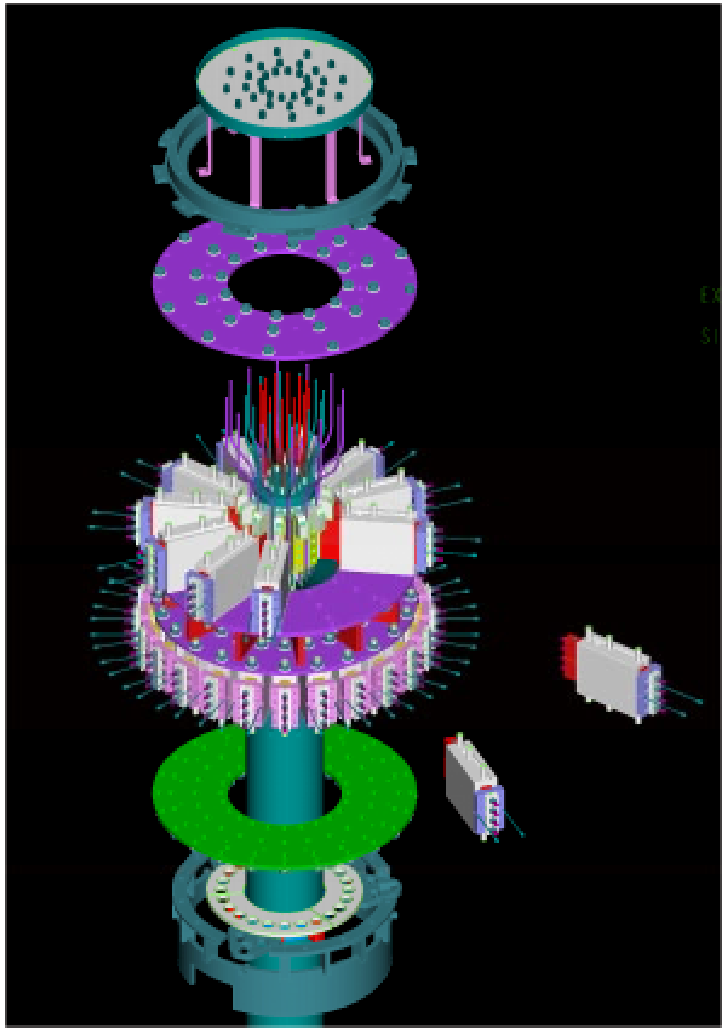


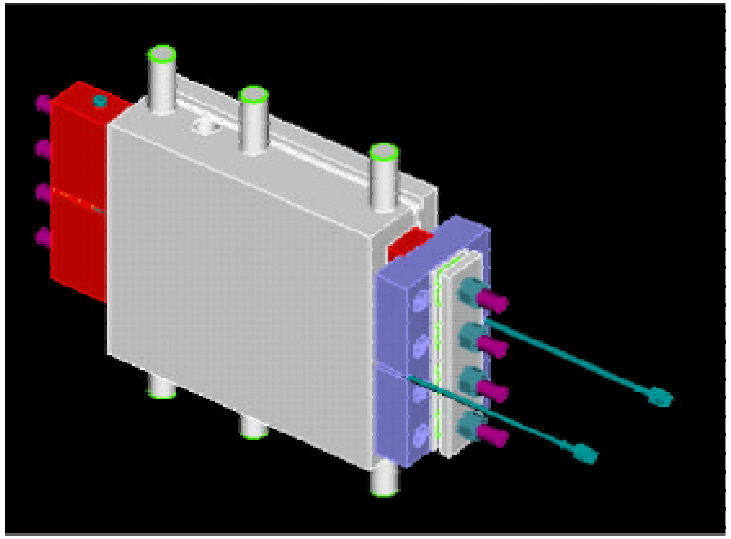


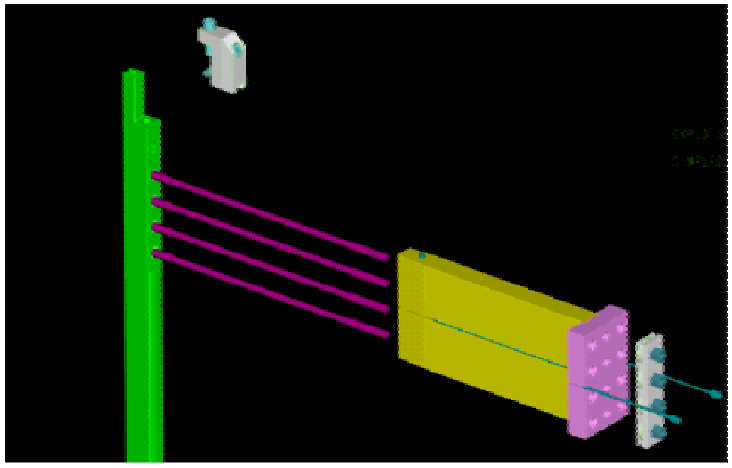
FEATURES OF NEW DESIGN



NEW TF JOINT DESIGN

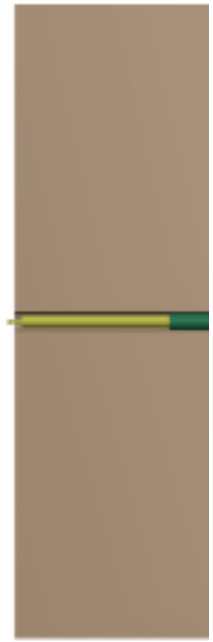


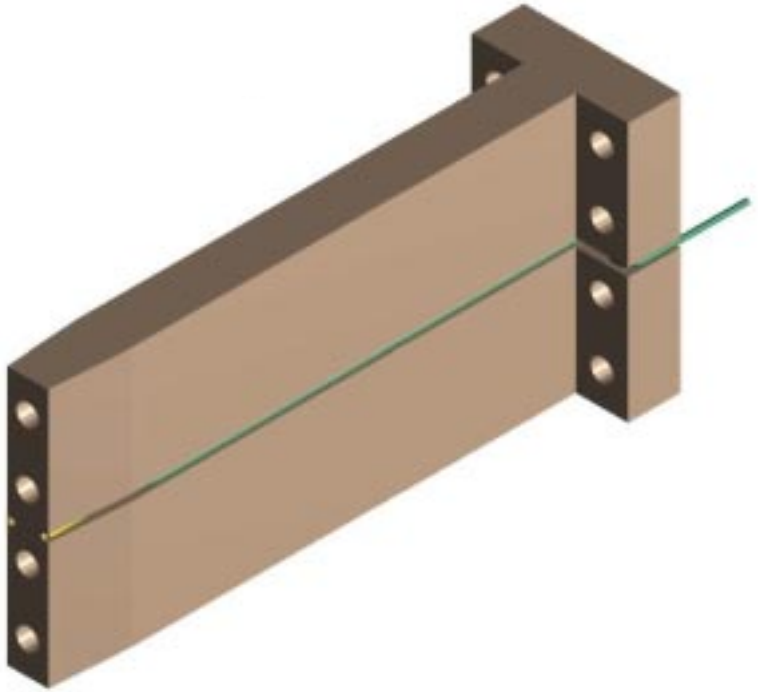




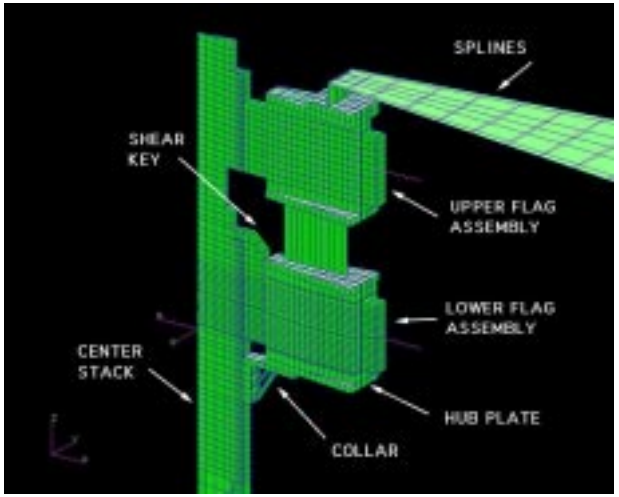
VOLTAGE PROBES FOR IN-SITU JOINT RESISTANCE MEASUREMENT

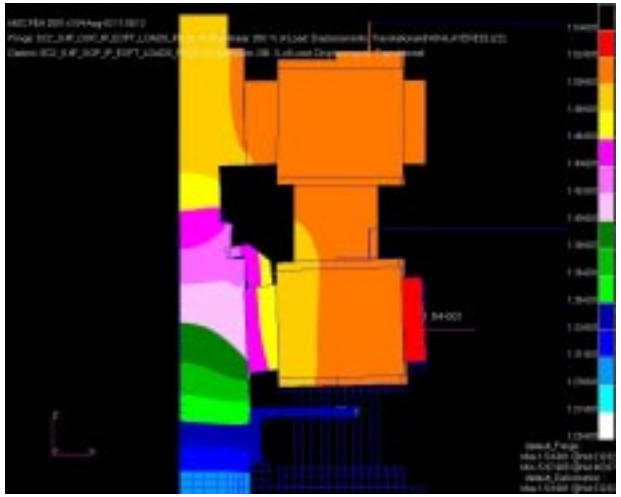
- commercial spring-loaded coaxial probe
- 2 probes per flag, 1 connected to instrumentation, 1 redundant spare
- all 72 joints monitored (maintenance @ 200A, real time at full current)

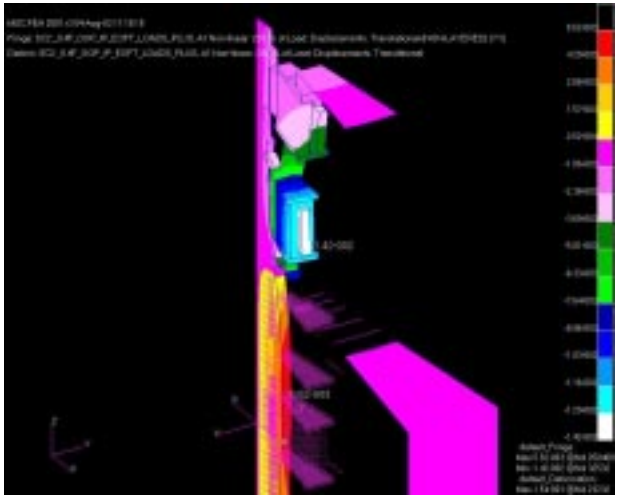


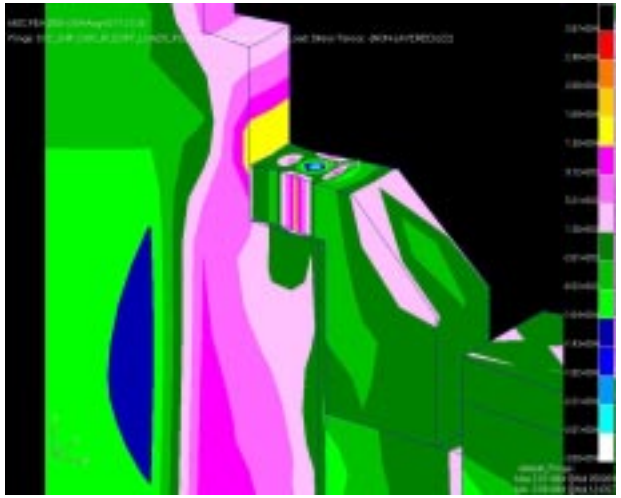


FEA USED TO ASSESS STRESSES, DISPLACEMENTS, CONTACT PRESSURES







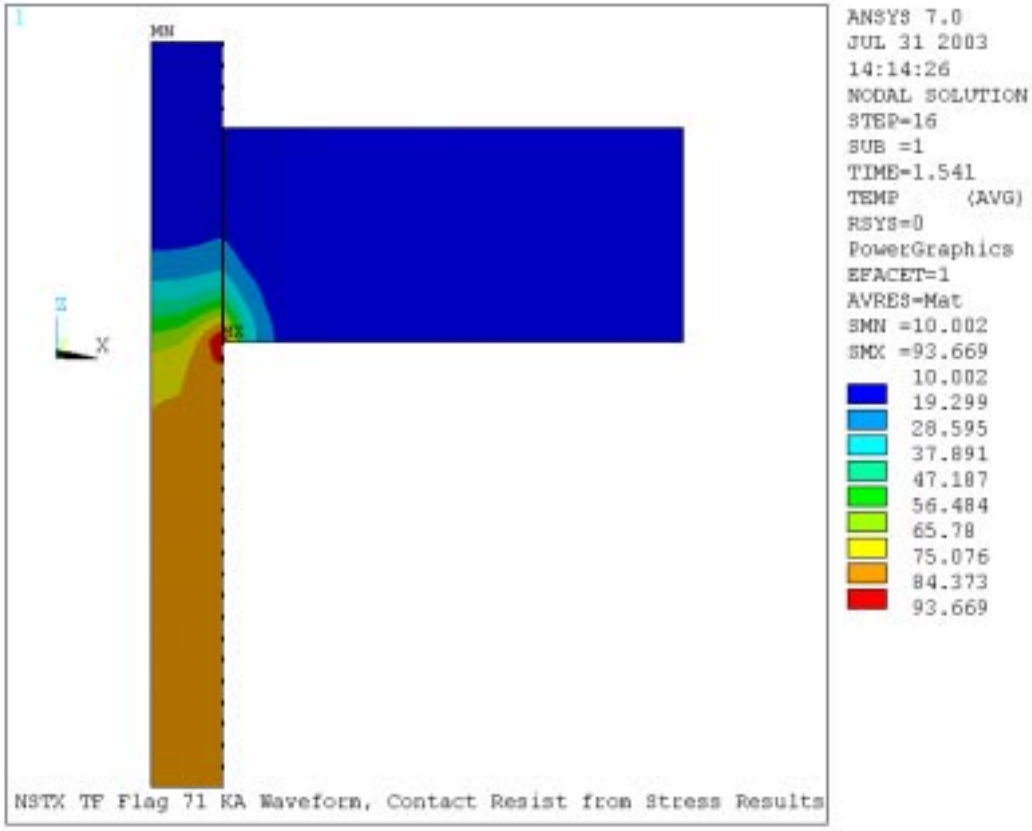


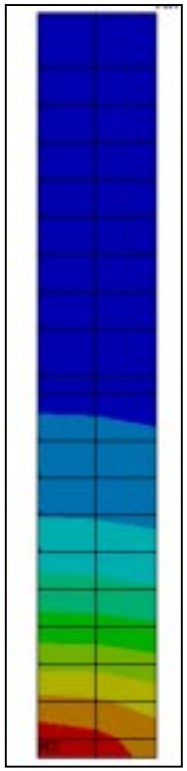
LOAD CASES EXAMINED

- Time Points
  - START OF FLAT TOP (SOFT)
  - END OF FLAT TOP (EOFT)
  - END OF PULSE (EOP)
- Conditions
  - Normal
  - Off Normal
    - ✓Low Preload (60%)
    - ✓High Friction Coefficient
    - ✓Low Friction Coefficient

THERMAL ANALYSIS

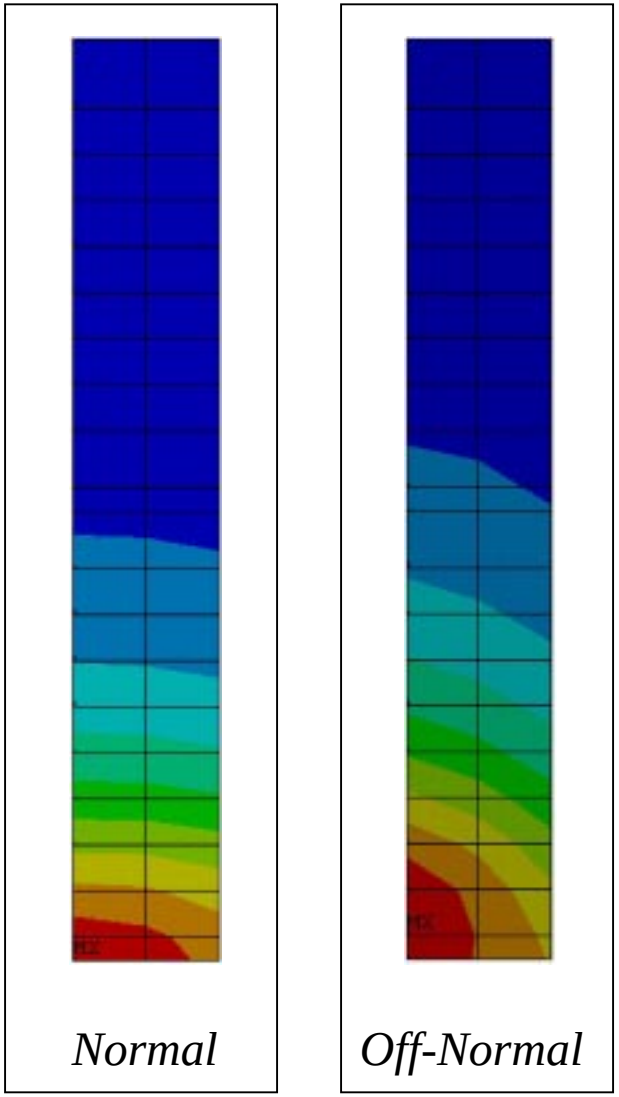
Max. Temperature of 94°C Well Below Limit of 120°C





Contact Region

OFF-NORMAL CASE: 60% PRELOAD



- Peak Temperature ≈ 3°C Higher
- Temperature Distribution Different
- Current Redistribution Beneficial

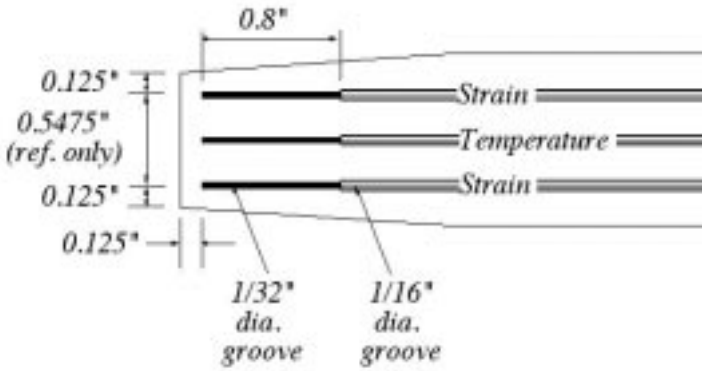
MAIN DESIGN IMPROVEMENTS

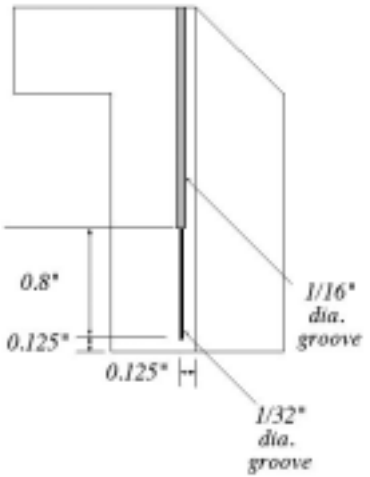
Feature	*Old Design*	*New Design*
Hub Stiffness	Lacking in Stiffness	Very stiff. Boxes form webs with disks like I-beams
Flag Bolts/Inserts	Four 5/16" bolts @ 2500#, marginal friction to carry shear	Four 3/8" studs @ 5000#, doubling of preload
	Dual purpose bolts, combined tension and shear functions	Shear Shoes
Shimming	Manually selected G10 shim stock	Flags potted in boxes
Resistance Measurement	10A Biddle measurement on disassembled joint, 1μΩ resolution	200A in-situ measurement ≈ 20x enhanced resolution, plus real time

All defects contributing to original failure have been addressed

FIBER OPTIC TEMPERATURE, STRAIN, DISPLACMENT MEASUREMENTS

- Four Flags (inner, outer, top, bottom)
- Hub and Flag twist angle (top, bottom)
- Spline (top only)

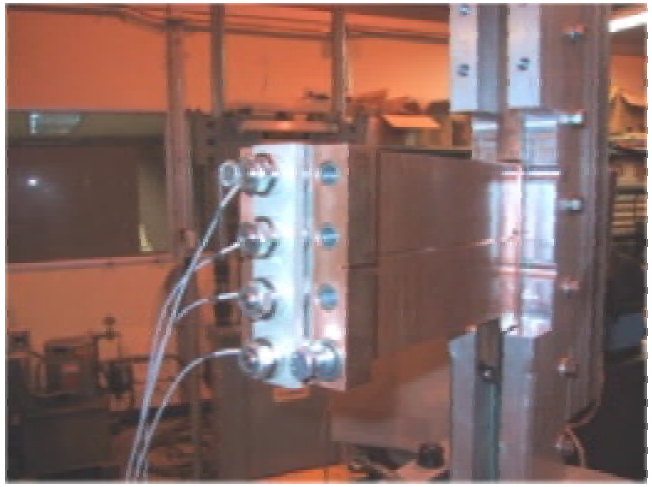




FISO Technologies, Inc.

PROTOTYPE TESTING

- Mechanical Tests
  - ✓ Full in-plane load, cycled
  - ✓ Full lateral load, static
  - ✓ 50,000 cycles
- Electrical Tests
  - ✓Full current at full I^2T
  - ✓Full in-plane and lateral load, static
  - ✓100 pulse current cycles



FABRICATION UNDERWAY AT PPPL






SCHEDULE

Present Status →

1.	TF Coil Repair Review	Apr ’03
2.	Complete 24 Outer Conductor Machining	Jun ’03
3.	Complete 12 Inner Conductor Machining	Aug ‘03
4.	TF Repair FDR	Aug ‘03
5.	Complete Insulating TF Conductors	Sep ‘03
6.	Complete Assembly/Mold of TF Bundle	Oct ‘03
7.	Test Inner TF Bundle	Nov ‘03
8.	Reinstall TF Bundle into center stack	Nov ‘03
9.	Begin Pre-Op ISTPs	Feb ‘04
10.	Ready for Plasma Operations	Feb ‘04
11.	Project Completion	Feb ‘04

Outage Duration ~ 1 year

CONCLUSIONS

- New Design Corrects All Defects of Original Design
- Follow-on Activities Will Increase Confidence
  - ✓ Mechanical Prototype Testing
  - ✓ Electrical Prototype Testing
  - ✓ Instrumentation During Commissioning and Operations
    - resistance measurement (200A maintenance and real-time) system
    - temperature, strain, displacement