TF Joint Operations Review
Introduction

- ✓Scope and Outline of Review
- ✓Summary of Findings from 2004 Run
- ✓Review of Joint Force, Pressure and Moment Concepts
- ✓Improvements made on Rebuilt Coil
- ✓Overview of New Analysis
- ✓New Operating Envelope

C Neumeyer

2/10/05

Committee Members

P Anderson (GA)
L Dudek (PPPL) - Chair
J Irby (MIT)
B Nelson (ORNL)
A Von Halle (PPPL)

Chit forms have been forwarded to off-site members

Scope of Review

- ✓ Declare targeted operating scenarios/envelope
- ✓ Provide justification for operating envelope
- ✓ Describe protection method to enforce operating envelope
- ✓ Describe commissioning plan

Outline of Review

- ✓Introduction (40 min)
- ✓Description of New Potting Process (30 min)
- ✓Simplified Modeling and Protection (30 minutes)
- ✓Commissioning Plan (20 minutes)
- ✓Summary (15 minutes)

2+ hours

Results from 2004 Operations

• Approximately 2800 pulses were executed with Bt ≤ 4.5kG (January - July)

• Measurements from initial commissioning results were not well understood and did not benchmark well with design basis (January- February)

• Efforts were initiated to develop refined analytic models and tools to promote better understand of behavior and interpretation of measurement data (February)

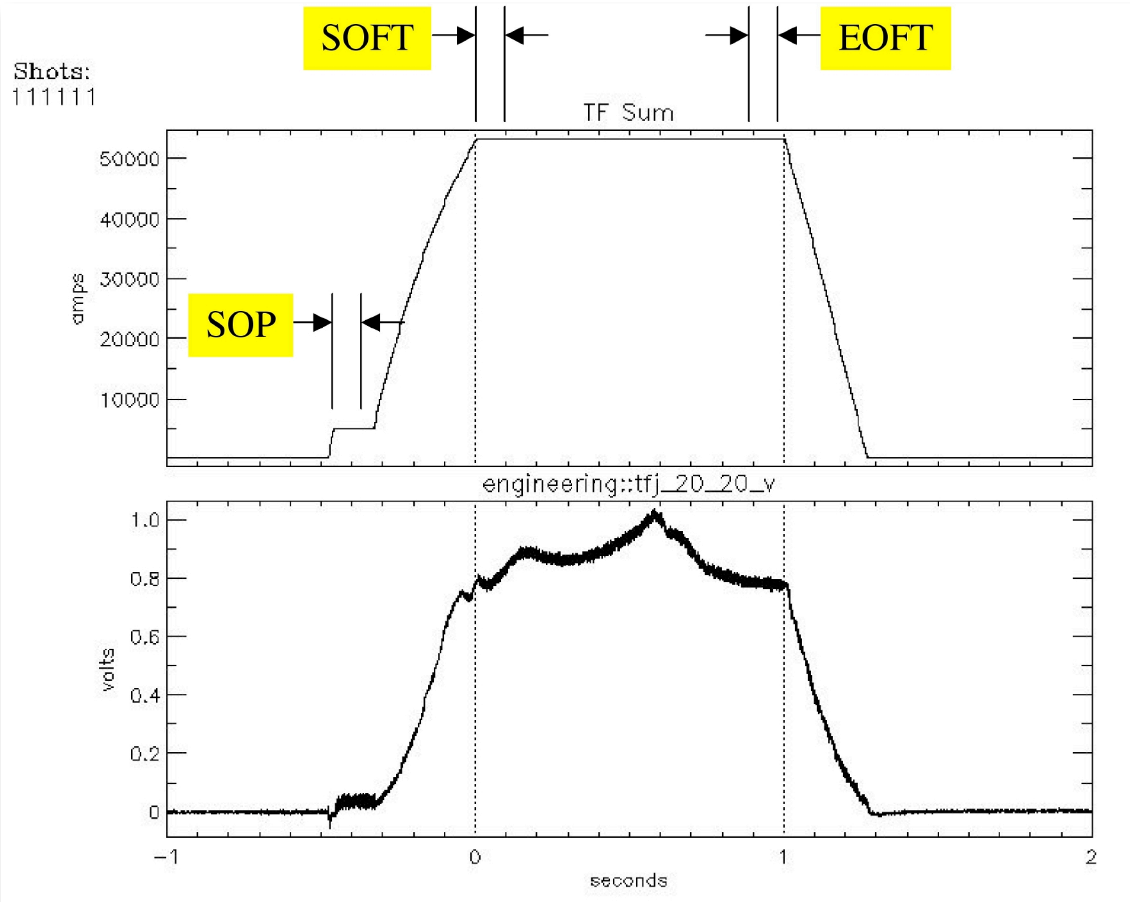
• Deeper understanding and tool development, along with upward trending of resistance data, led to concern that structural support system was not functioning properly (June)

•Additional measurements were made which confirmed excess motion of flags and excess moment being applied to joint (July)

• Operating level was reduced to Bt ≤ 3.0kG after ~ 2200 shots (July)

• Disassembly revealed defects in potting of flags in boxes, along with pitting on the contact surfaces (August)

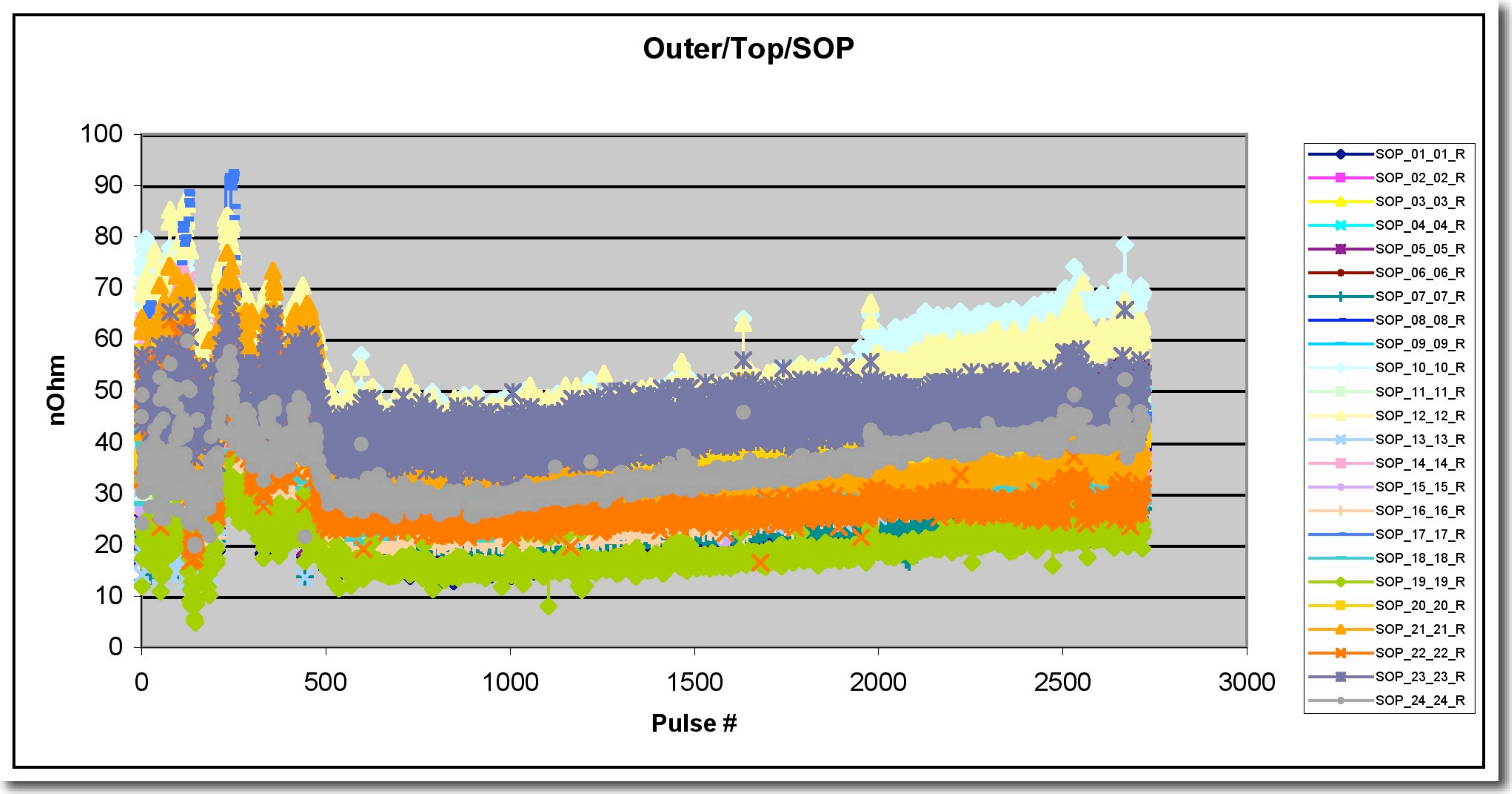
Trending Measurements



- Resistance Measured At 5kA At Start of Pulse (SOP) And At Other Times (SOFT, EOFT) During Pulse

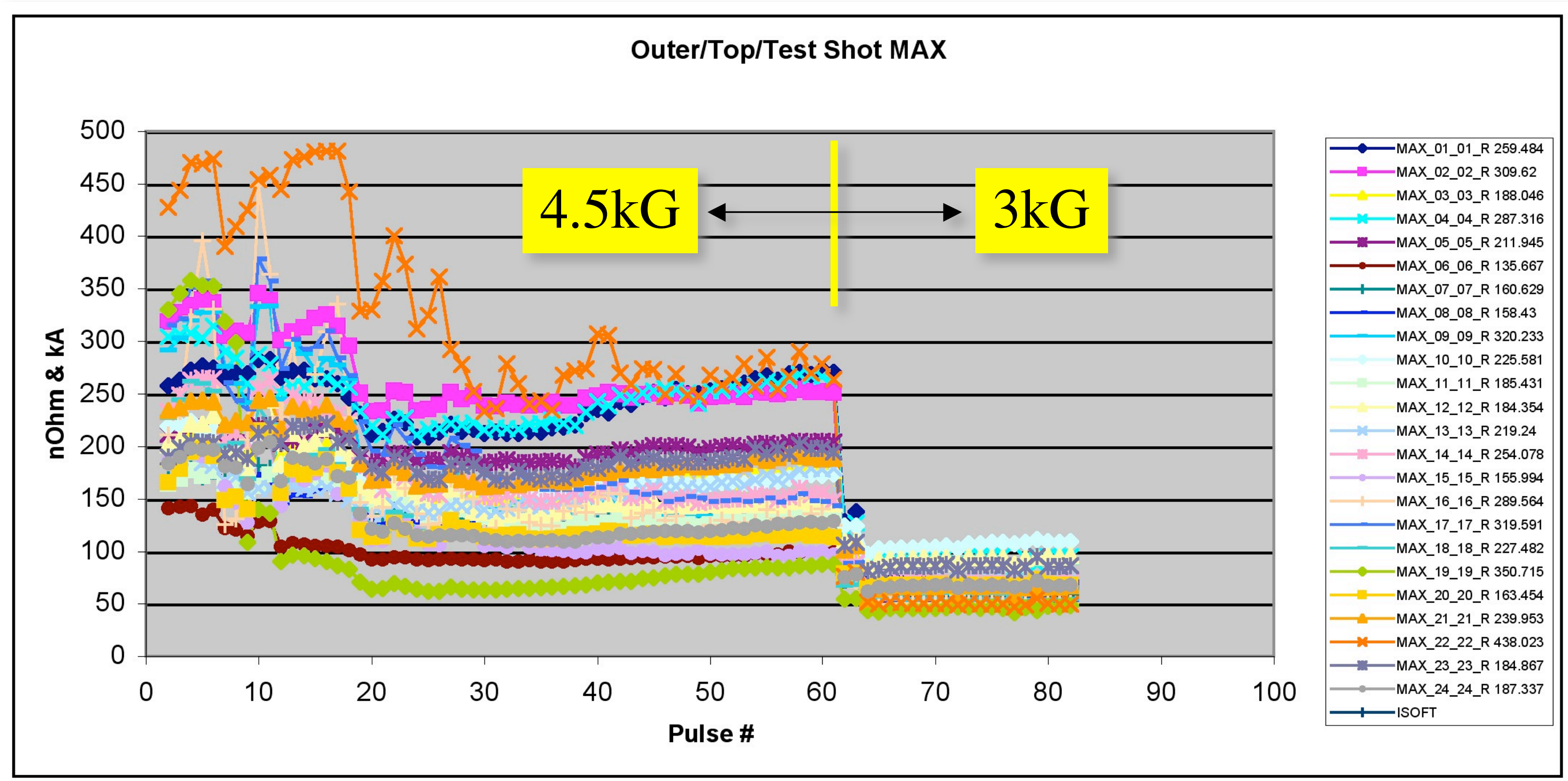
- Maximum (MAX) Also Recorded Each Pulse

Typ. Resistance Trends at 5kA Pedestal



Includes all test shots and plasma shots

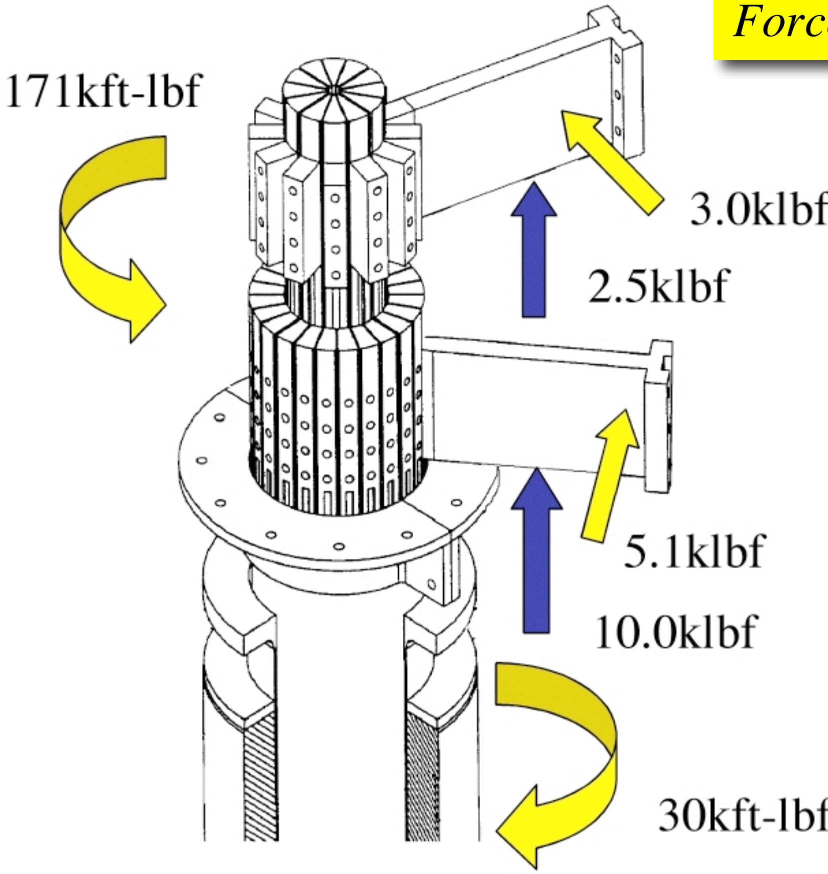
Typ. Max Resistance During Test Shots



Includes test shots only

JxB Forces on Flags and Bundle

Forces noted are maximum possible values

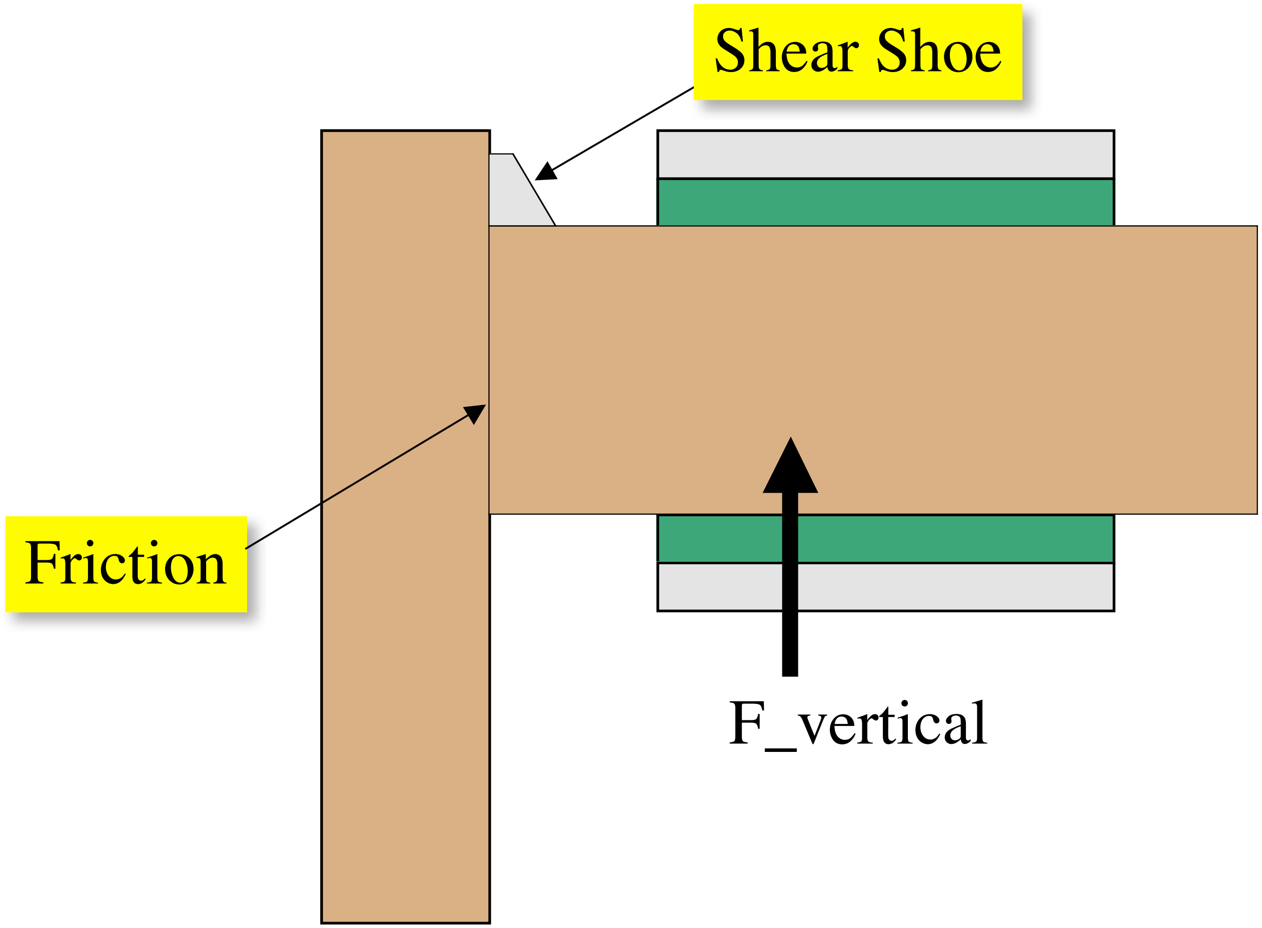


- In-Plane
  - -vertical load and moment due to magnetic pressure from self-field
- Out-of-Plane
  - -lateral due to $I_{tf} x B_{z(oh\&pf)}$
  - -torsional due to $I_{tf} x B_{r(oh\&pf)}$

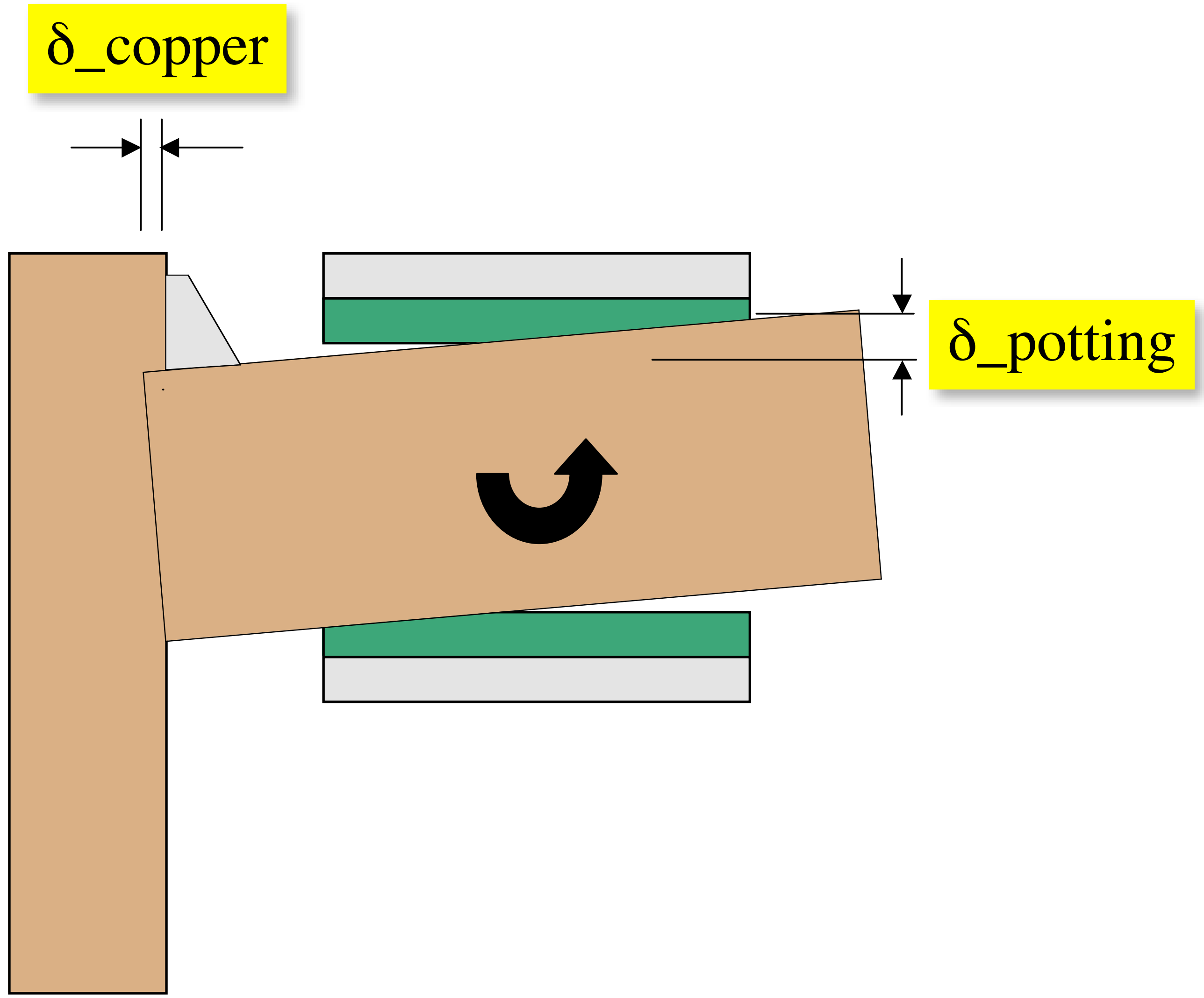
Notes:

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

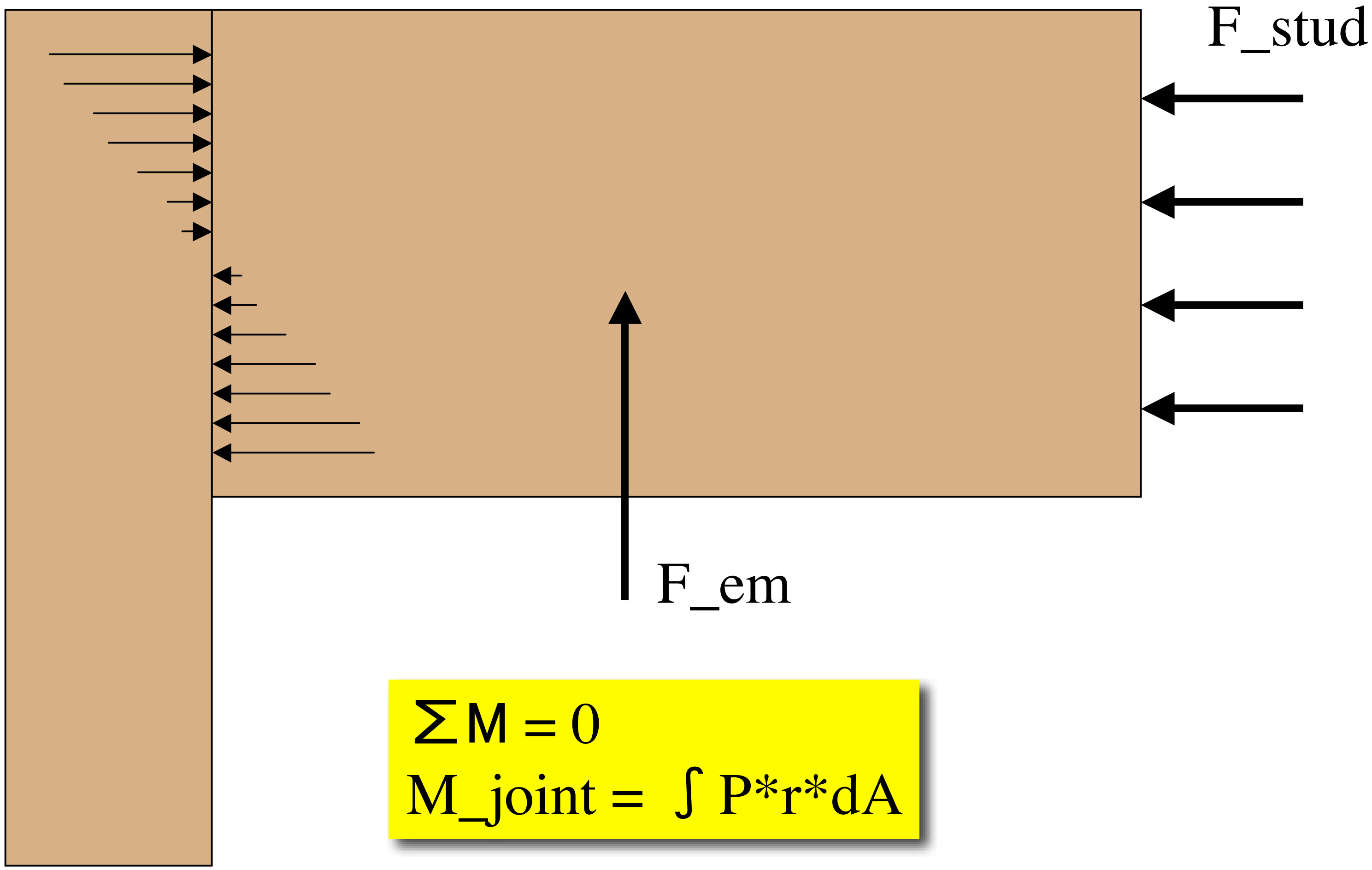
Vertical Loads Taken By Friction and Shear Shoe



Moments Shared by Structure and Joint



Moment Reacted at Joint Related to Pressure Distribution



$\Sigma M = 0$

$M\_joint = \int P*r*dA$

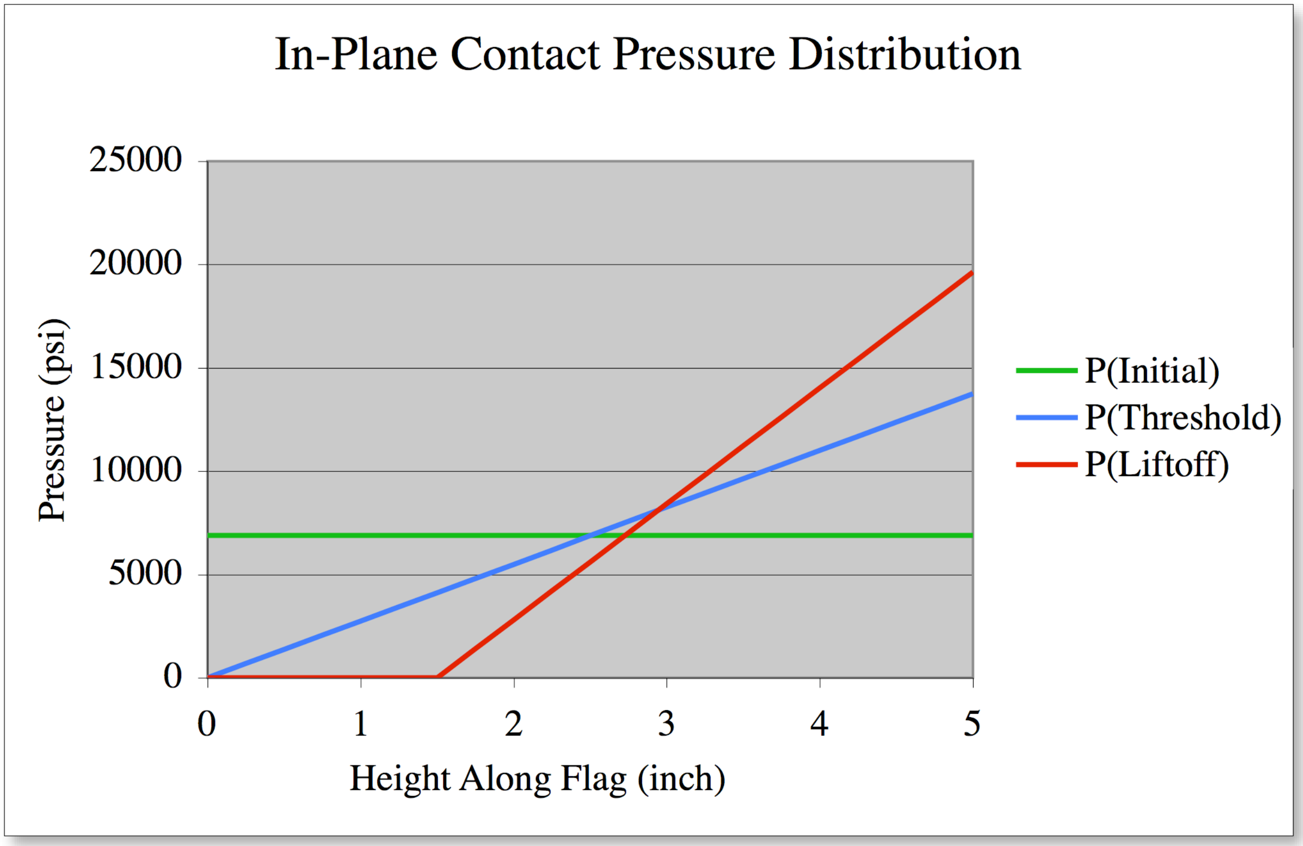
Reaction of Moment By Potting Is Key Factor in Joint Behavior

Excess moment leads to skewed pressure distribution and…

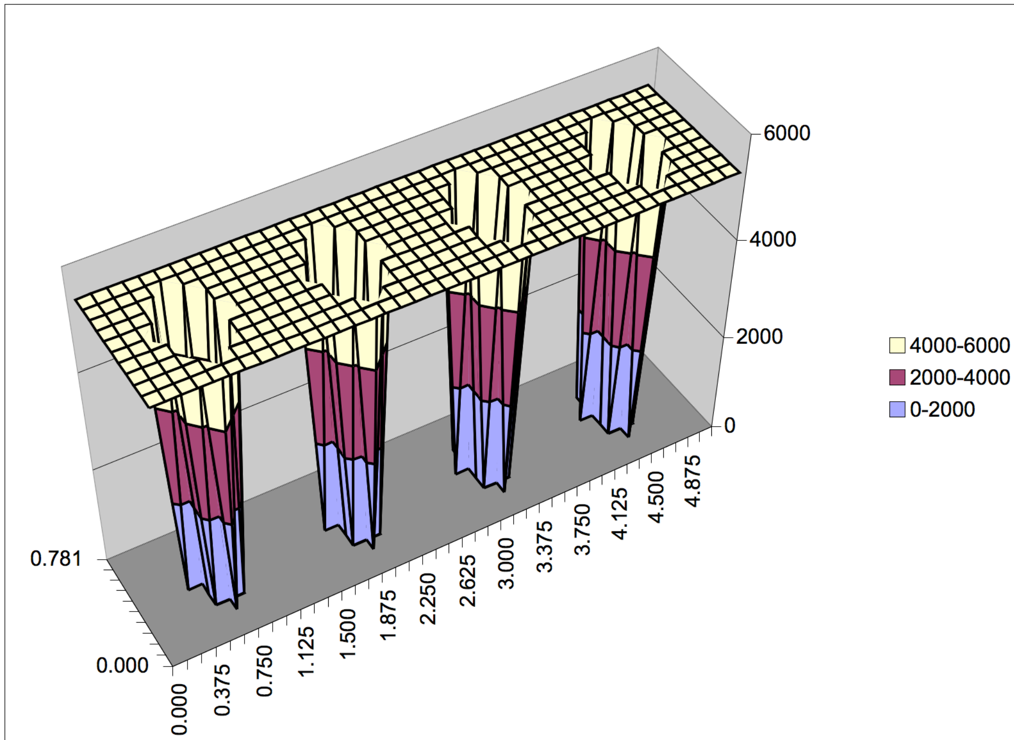
- shift in current pattern
- liftoff during pulse
- excess copper stress

Contact Pressure Distribution is Key Factor

2D Concept of Contact Pressure and “Liftoff”

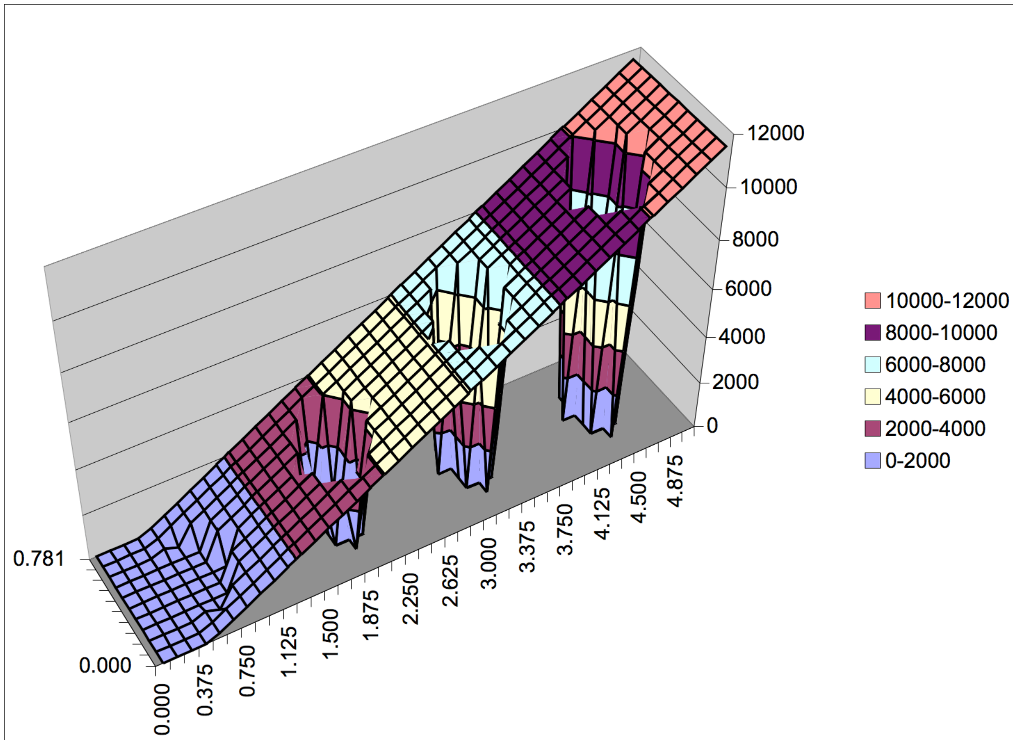


3D Pressure Distribution at Joint - Initial



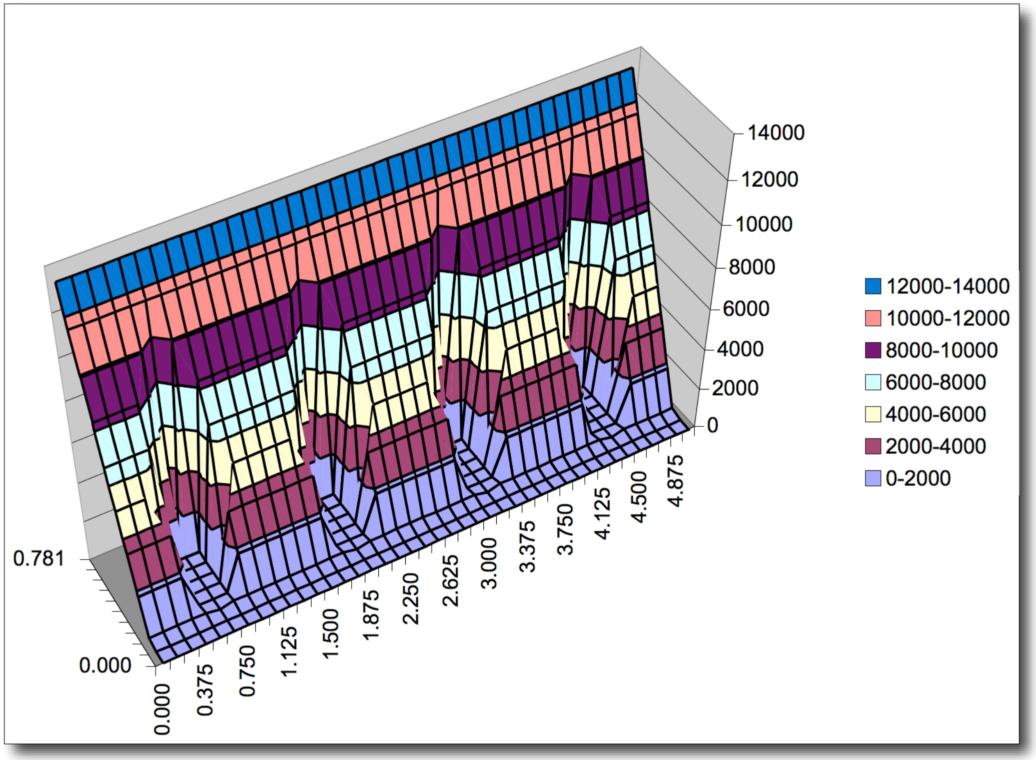
Initial Pressure ~ 5ksi

3D Pressure Distribution at Joint: In-Plane Only



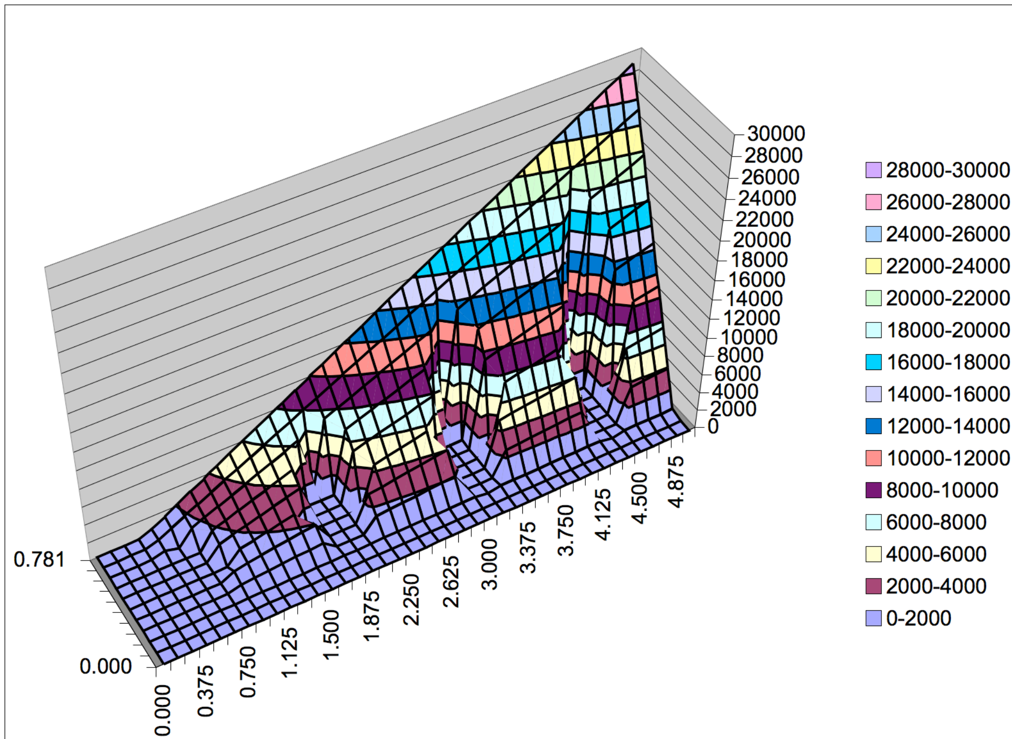
In-Plane Effect

3D Pressure Distribution at Joint: Out-of-Plane Only



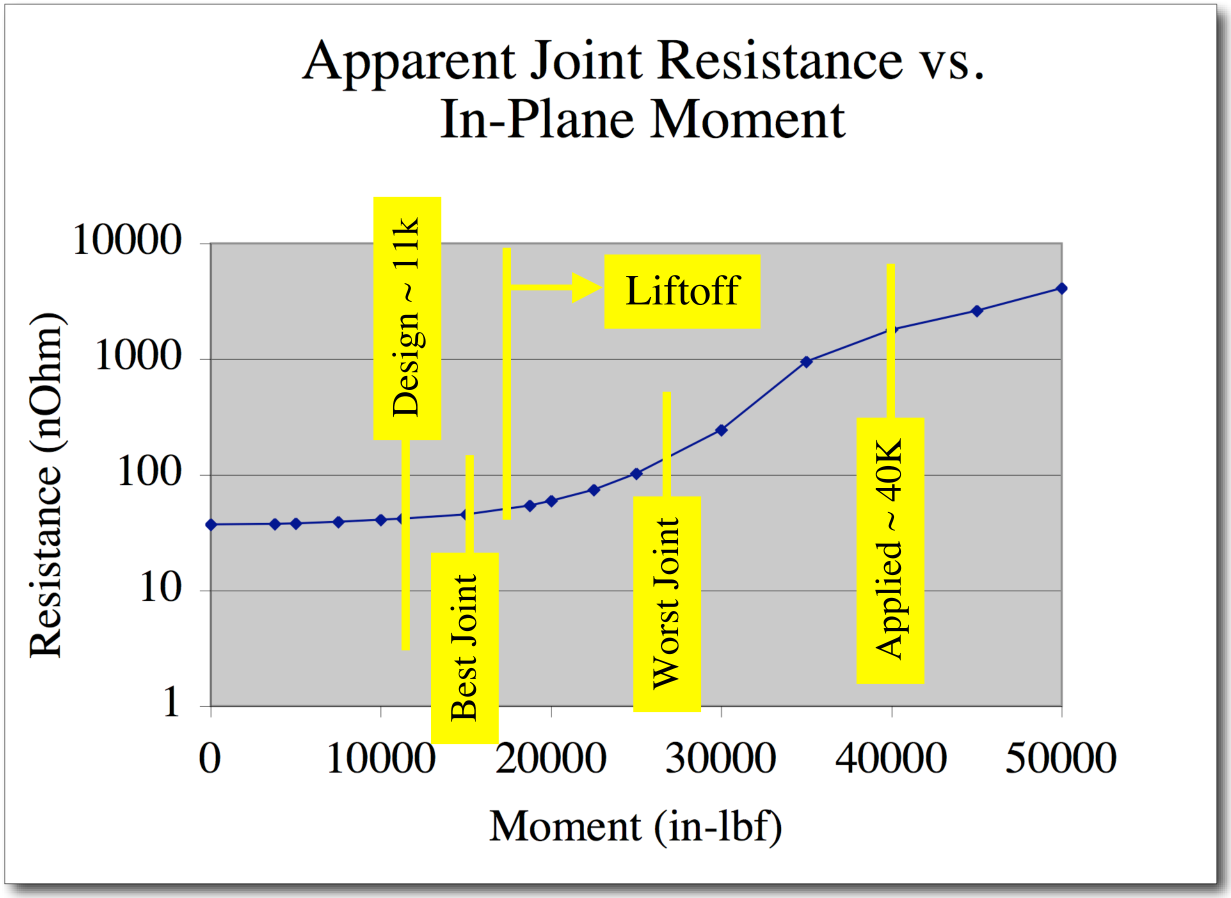
Out-of-Plane Effect

3D Pressure Distribution at Joint: Combined Loading

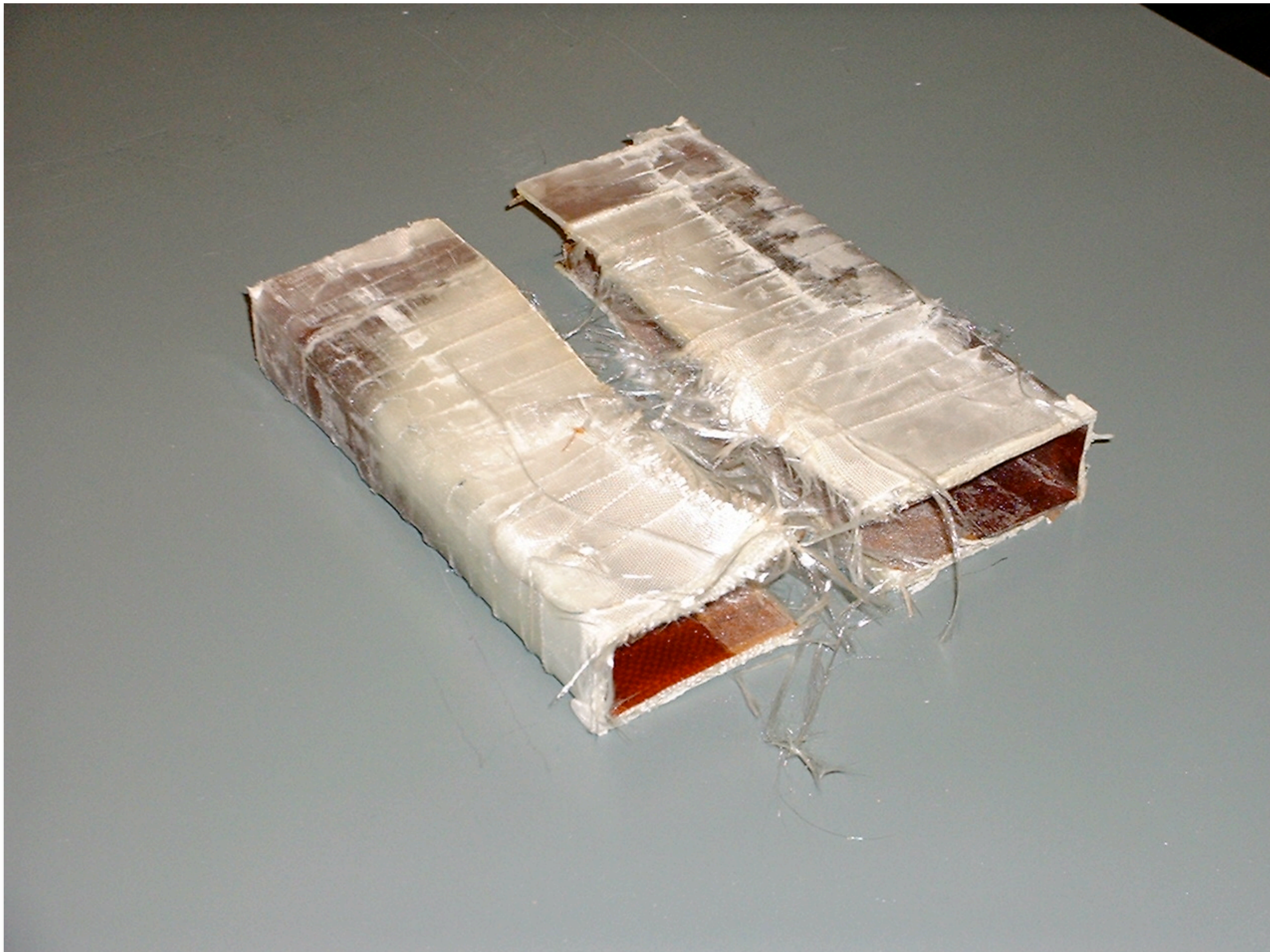


Combined Effect

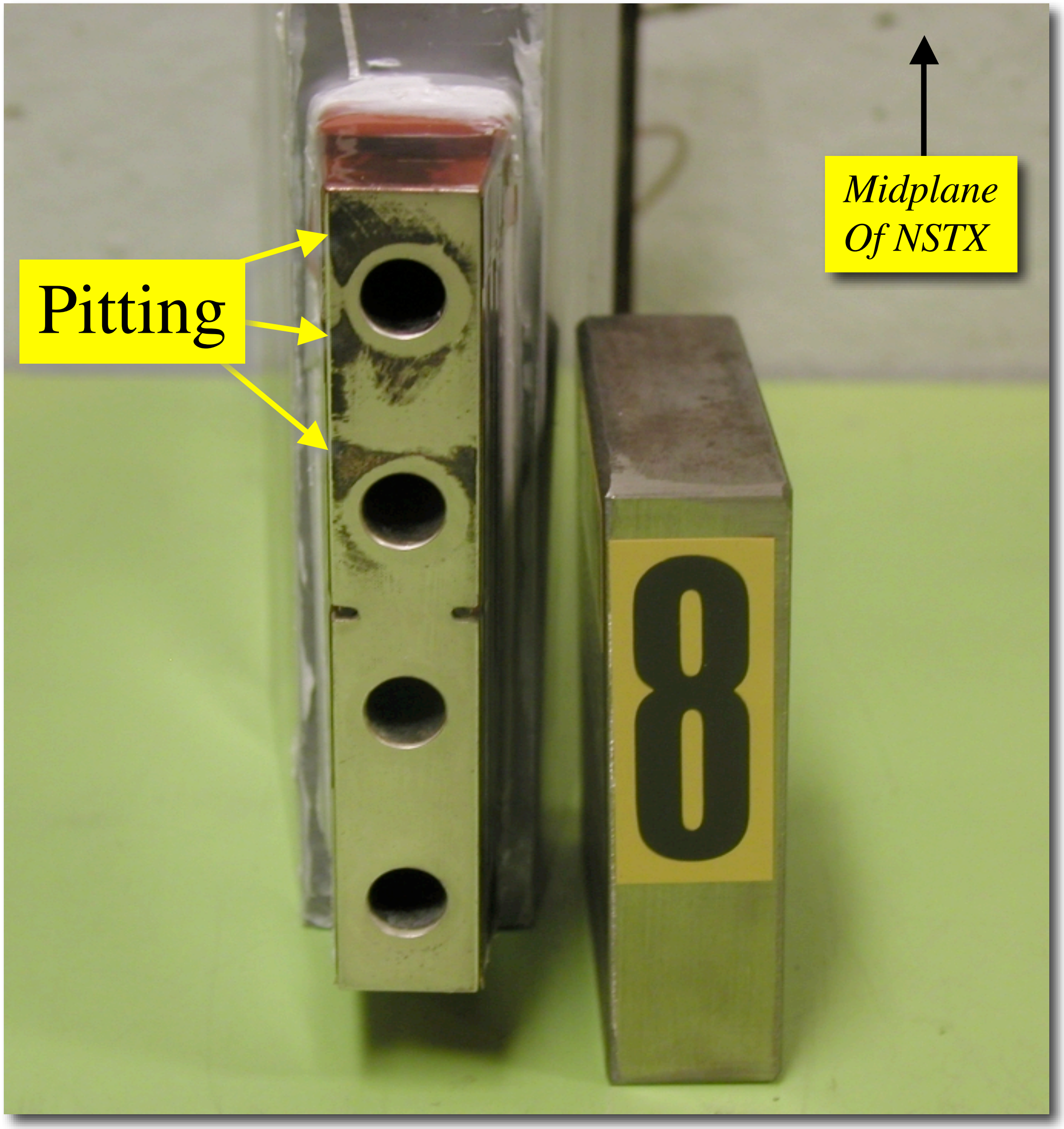
Analysis During Last Run Showed That Structure Was Not Reacting the Moment As Intended



Potting Was Found to be Defective



Liftoff of Joint Led to Pitting Damage



- There was a wide range in degree of pitting damage
- This joint is one of the worst examples
- This is not a new phenomenon

Effect of Liftoff and Pitting

• Based on prior run, we do expect pitting phenomenon to occur with liftoff

• Pitting should occur to a much lesser degree with potting improvements

• We anticipate that this type of phenomenon will stabilize after some erosion takes place, and that current will find alternate pathways in regions not subject to liftoff (z_{flag} >> liftoff length)

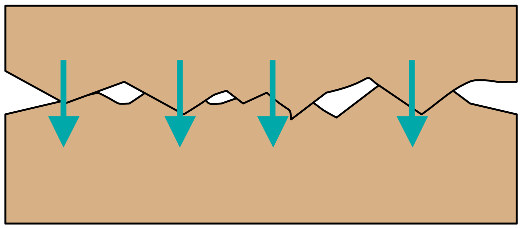
• Exact mechanism is not known but two theories have been hypothesized

-microscopic pinching off of current pathways

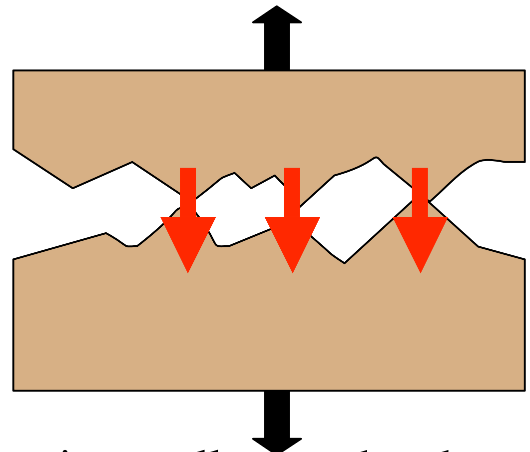
-macroscopic instability due to high current density

Theories to Explain Pitting

• Surface peaks (asperities) at microscopic level become disconnected leading to current pinching and small melt regions

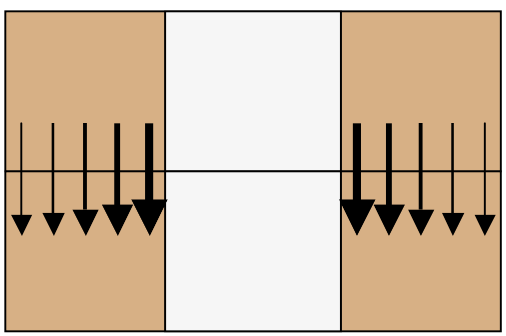


Before Liftoff, low current density

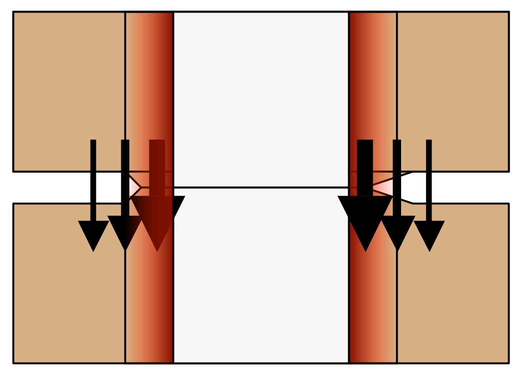


During Liftoff, high current density and circuit breaking, local melting

• Small localized regions with high current density swell up as they heat more than surrounding areas, increasing local contact pressure, increasing local current density, and so on, in an unstable fashion



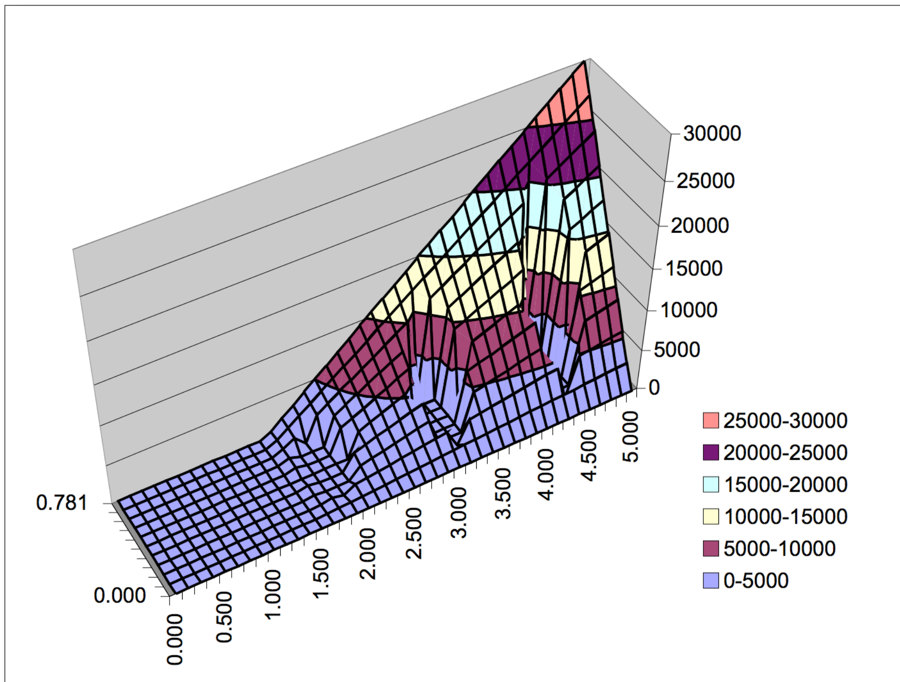
High current density, e.g. near holes



Swelling, increased pressure and conductivity,

These are hypotheses, not proven

Models would Predict Local Yielding on Some Joints, However, No Visible Evidence



Worst case joint IP moment ~ 27kin-lbf
(67% of IP moment to joint instead of 29% expected)
Local Pressure > 30ksi assuming 2.7kin-lbf OOP moment

Repair of Contact Surfaces

• Pitted contact surfaces on flags were re-machined

• Pitted surfaces of bundle conductors were manually honed (high spots removed)

• All flags were measured, and the worst case out-of flatness measurement on the flag surfaces after machining was 1.1 mil

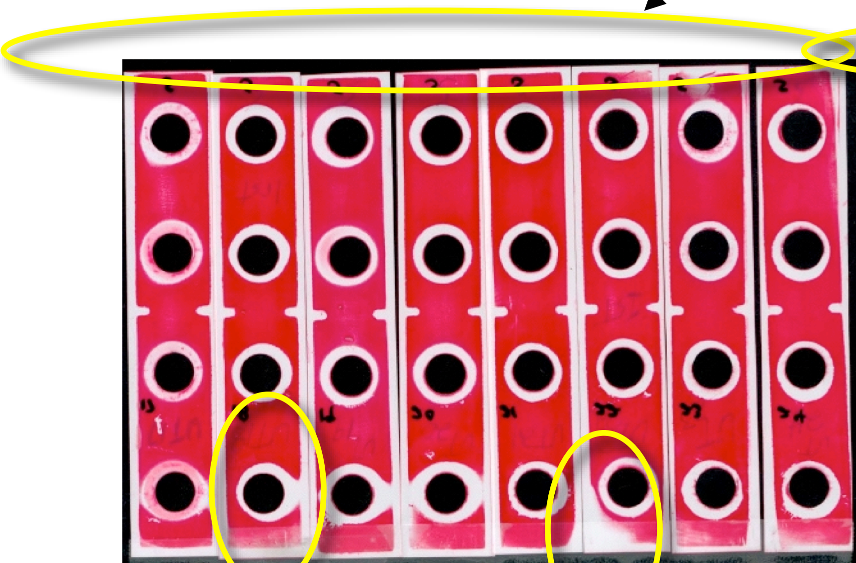
• Two of the bundle contact surfaces were measured for flatness down the center and were within 2 mils

• This slightly exceeds original drawing spec of 1 mil

• Pressure sensitive paper was used to assess all joint fit-ups after re-work

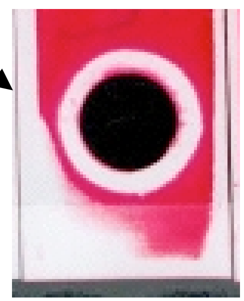
Condition of Repaired Surfaces

No obvious indication of deformation at corners

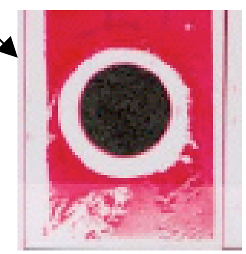


Midplane

Area missing around insert



Corner defect due to original out-of-flatness and/or manual re-working



Areas eroded by Pitting, then reworked

Effect of Surface Irregularities

- We anticipate that contact regions lost to surface irregularities are tolerable since current will find alternate pathways in regions further up the flag

- We anticipate that pitting will stabilize because current will eventually avoid eroded areas and find alternate pathways in regions further up the flag

- Structural integrity of joint is not significantly effected by surface irregularities

- Area lost around inserts is probably most critical, will cause higher local temperatures than predicted in analysis

- Analysis of joints with missing contact area has not been performed

Flag Stud and Insert Stresses

•Although more moment was transmitted to joints than intended, axial loads on flag studs and inserts did not exceed design value

• Moment induced load on flag and stud in parallel (~ equal strain) reduces compression on flag and increases tension on stud

• Most of load reaction comes from flag due to lower elasticity of flag vs. stud/belleville washer stack

• Design basis (NASTRAN) ΔF ~ 200lbf over 5klbf preload

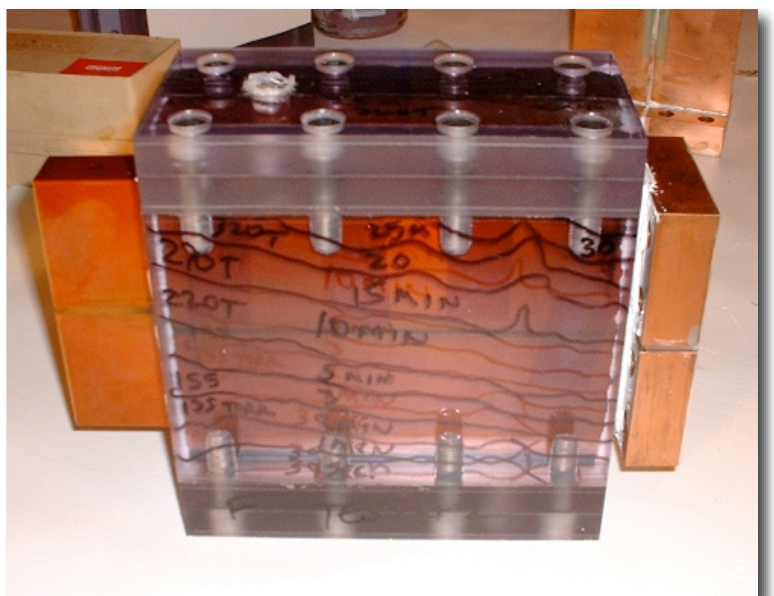
• Fatigue (design and test to 100kcycles) based on ΔF = 1klbf

• NASTRAN (run 64N) for no-potting case at 4.5kG is ΔF = 850lbf

Potting Improvements

Extensive development program was conducted to optimize potting process

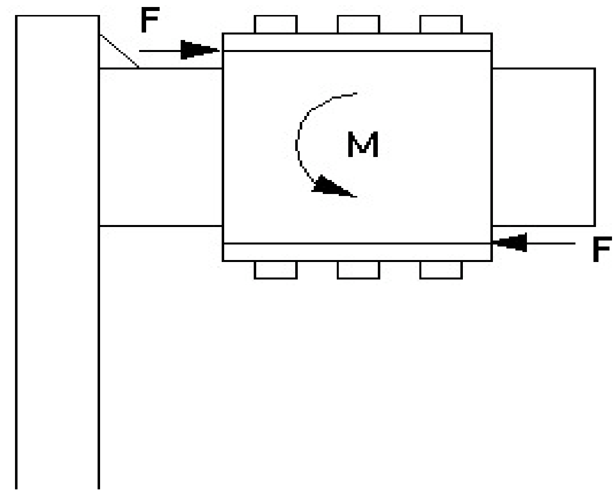
- improved vacuum seals
- improved electrical insulation
- different resin (long pot life)
- improved process
- all potted flags will be tested for mechanical properties

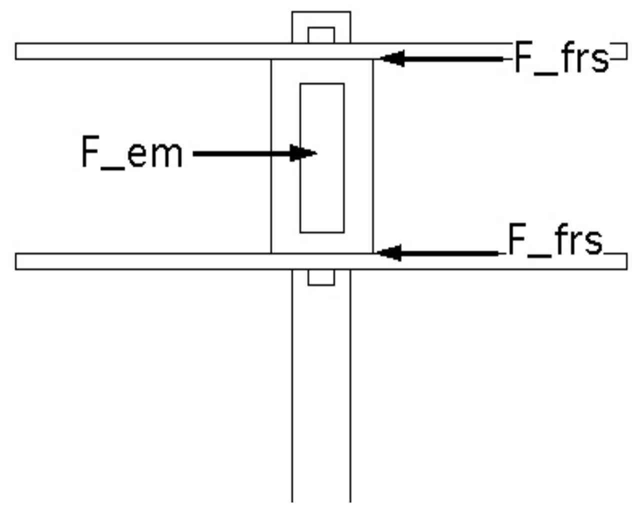


Hub Disk Improvements

High friction coating developed to enhance friction shear interface between hub disks and flag boxes

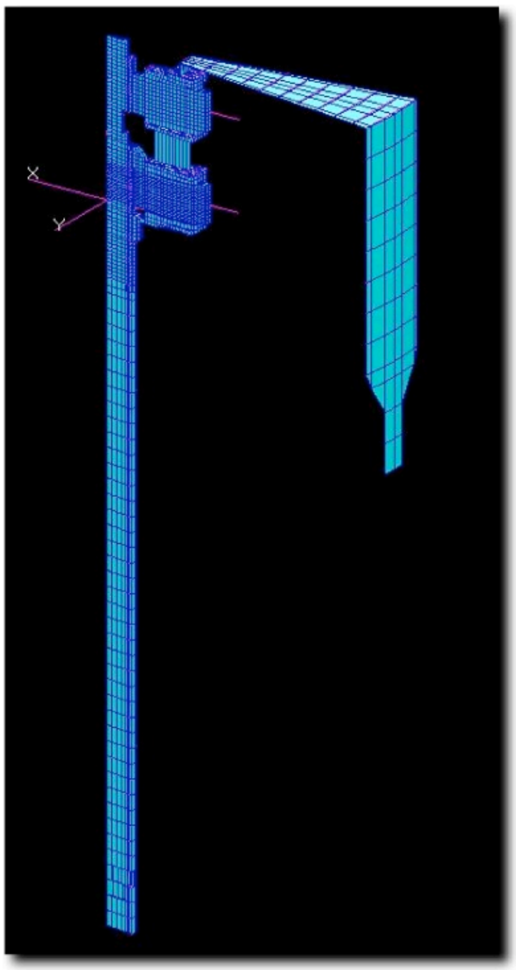
- diamond grit coating
- full scale mock-ups tested at PPPL
- COF > 0.5 (~ 2x base SS COF)
- design review held on 10/27/04

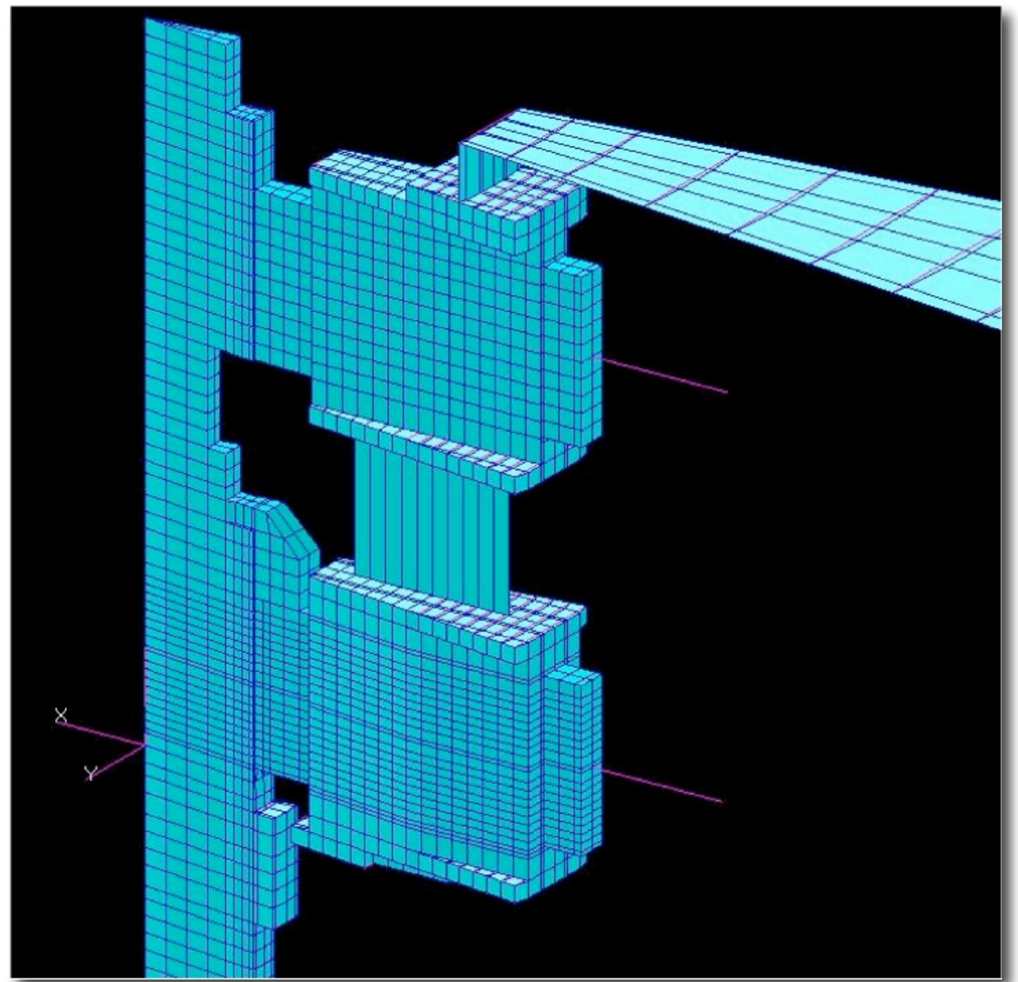




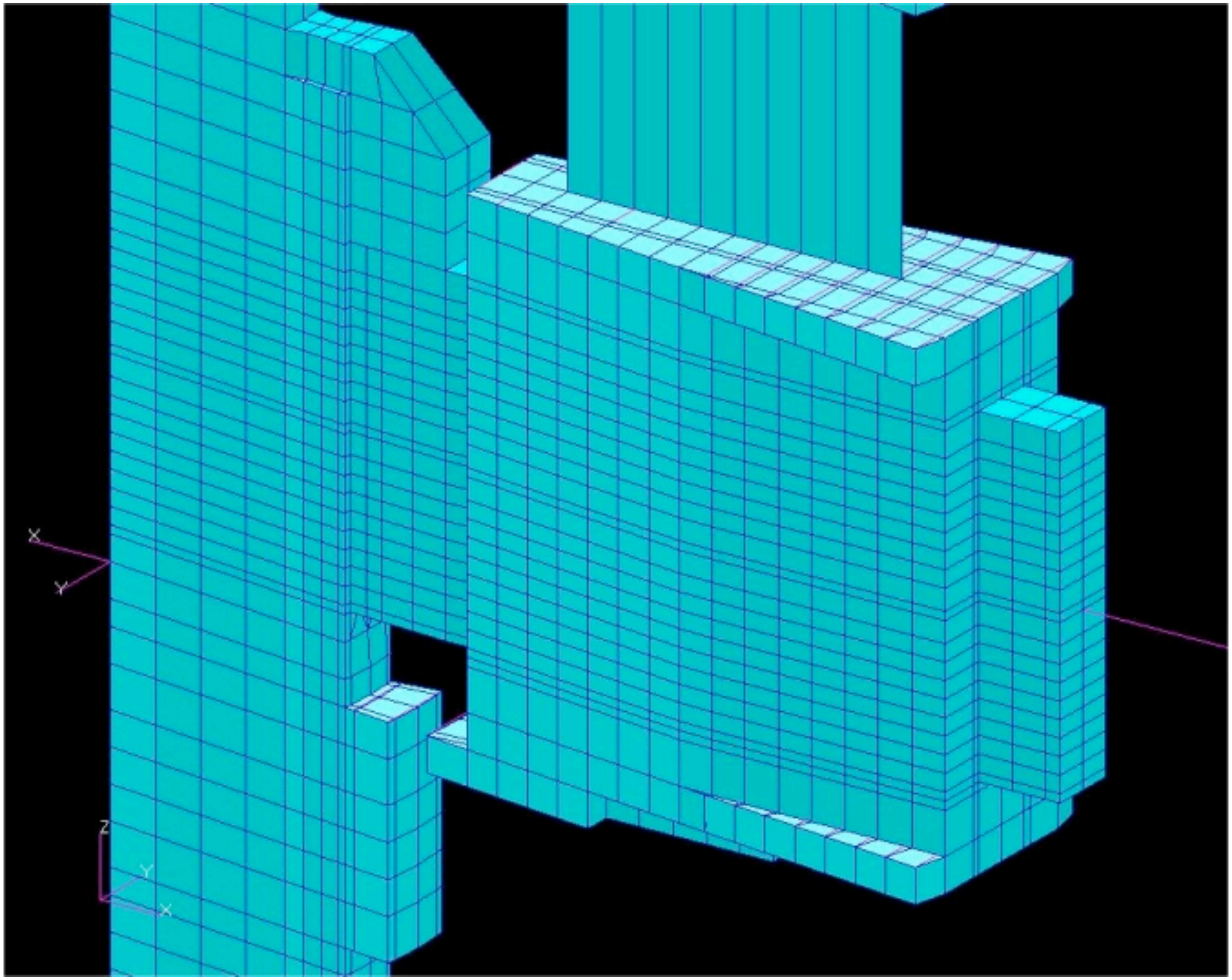
New Analysis - Structural

- NASTRAN (I Zatz)
  - ✓ increased mesh density at joint
  - ✓ included additional length of flex link in force calculation
  - ✓ incorporated revised PF1a coil in force calculation





New Analysis - Structural



New Analysis - Structural

- No significant differences from findings reported at August '04 FDR
- More cases run and more data extracted
- Developed influence matrix for in-plane and out-of-plane moments at joint

RUN CASE	OUTER FLAG IN-PLANE MOMENT (in-lbs)	OUTER FLAG O-O-P MOMENT (in-lbs)
4.5 kG – SOFT – No PF – Run 47NA	**11490**	**-**
4.5 kG – SOFT – 100% PF – Run 70N	**10920**	**2667**
4.5 kG – OHSS – 100% PF – Run 71N	**10430**	**2827**
4.5 kG – EOFT – 100% = No PF – Run 48N	**10340**	**13**
4.5 kG – SOFT – 24 kA OH, only – Run 72N	**10810**	**2542**
4.5 kG – SOFT – 5 kA PF3, only – Run 73N	**11461**	**179**
4.5 kG – SOFT – 5 kA PF1A, only – Run 74N	**11460**	**33**
4.5 kG – SOFT – 10 kA PF2, only – Run 77N	**11390**	**461**
4.5 kG – SOFT – 20 kA PF5, only – Run 78N	**11360**	**336**
6.0 kG – SOFT – 100% PF – Run 75N	**17770**	**3390**
6.0 kG – OHSS/EOFT – 100% PF – Run 76N	**10340**	**3424**

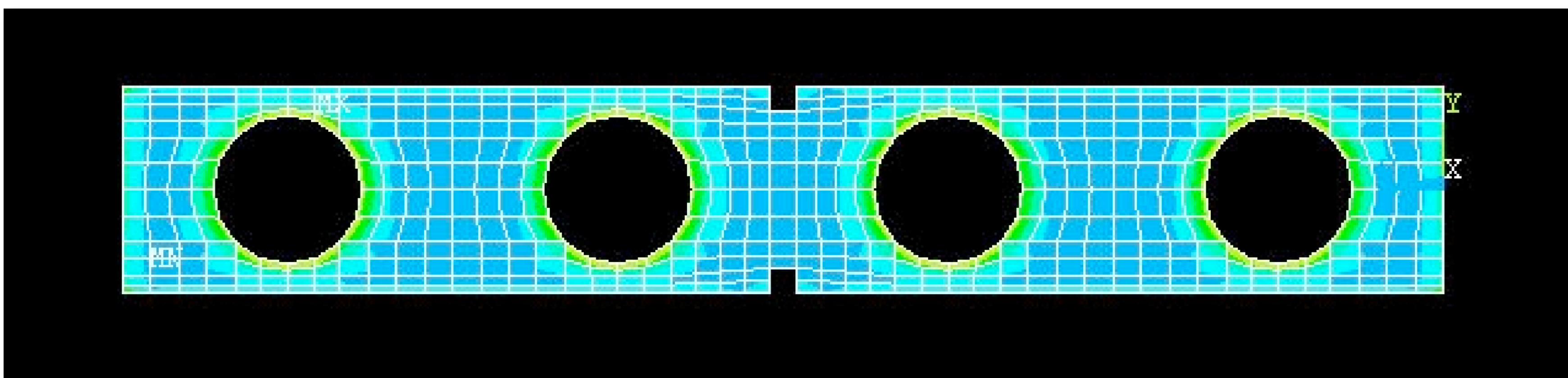
New Analysis - Joint Behavior

•ANSYS

✓ Developed fine mesh 3d ANSYS model of joint

- Captures nuances of pressure distribution and conductivity near inserts and at corners

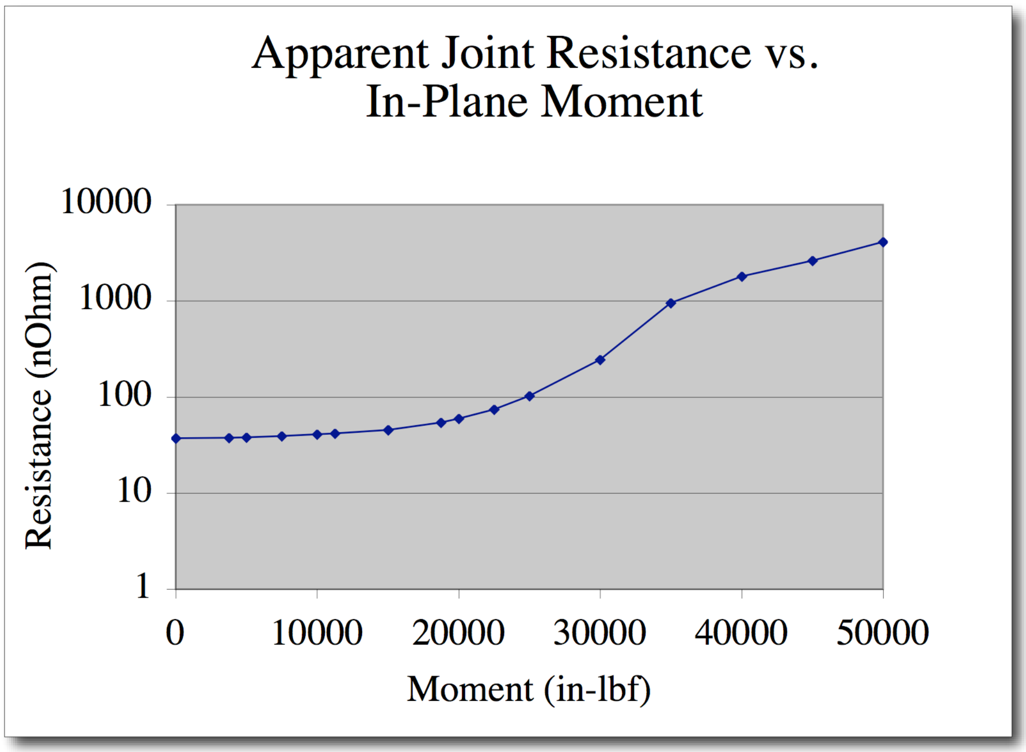
- Used to develop “Rosetta Stone” translation data base of apparent resistance measured by voltage probe vs. in-plane and out-of-plane moments at joint



New Analysis - Joint Behavior

- MATLAB

  ✓ Developing tools for "data mining" of MDS+ voltage probe measurements so actual in-plane and out-of-plane moments at joint can be extracted from voltage data and performance of structure can be assessed.



New Analysis - Electrical/Thermal

- FEMLAB

  ✓Developed 2d and 3d models of joint including transient electrical and thermal analysis with in-plane moments and TF current applied as a function of time

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- FEMLAB

  ✓Developed 2d and 3d models of joint including transient electrical and thermal analysis with in-plane moments and TF current applied as a function of time

Target Operating Envelope - 4.5kG

- $Bt \leq 4.5kG$

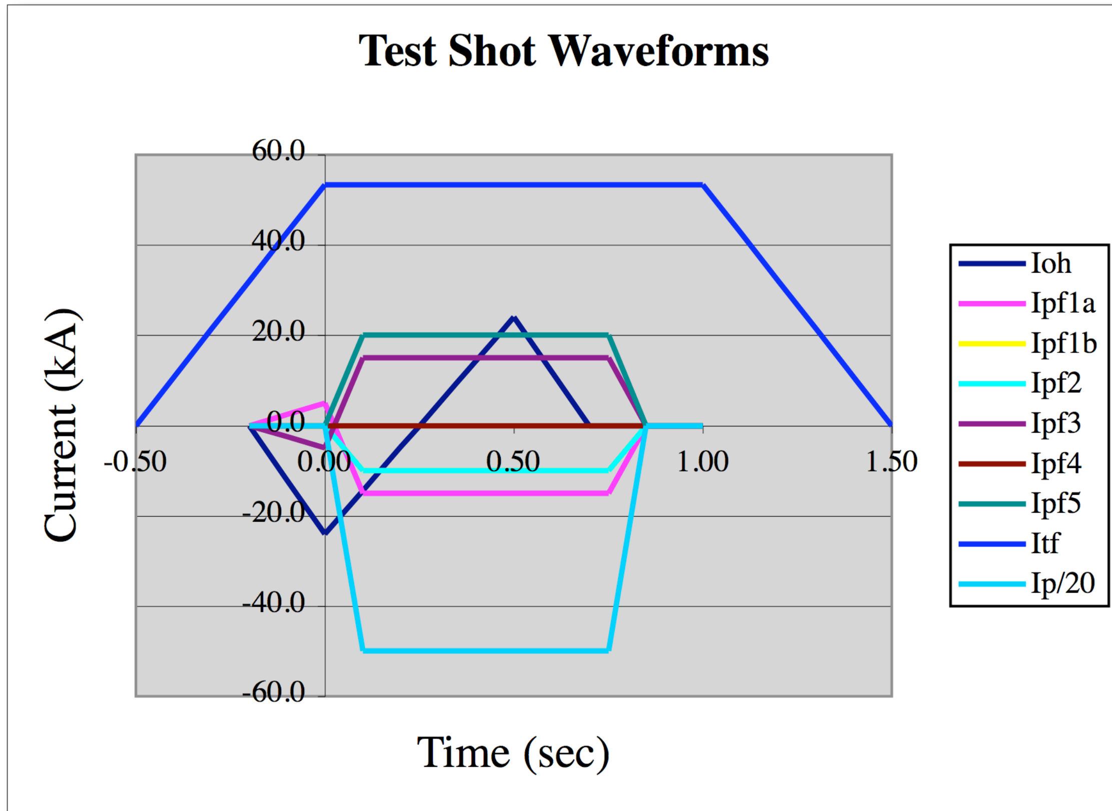
- 1.0 second flat top

- full OH (-/+24kA)

- other PF's…

  |I_pf1a| ≤ 15kA
  |I_pf1b| ≤ 10kA
  |I_pf2| ≤ 10kA
  |I_pf3| ≤ 15kA
  |I_pf5| ≤ 20kA

- test shot waveform timing as indicated



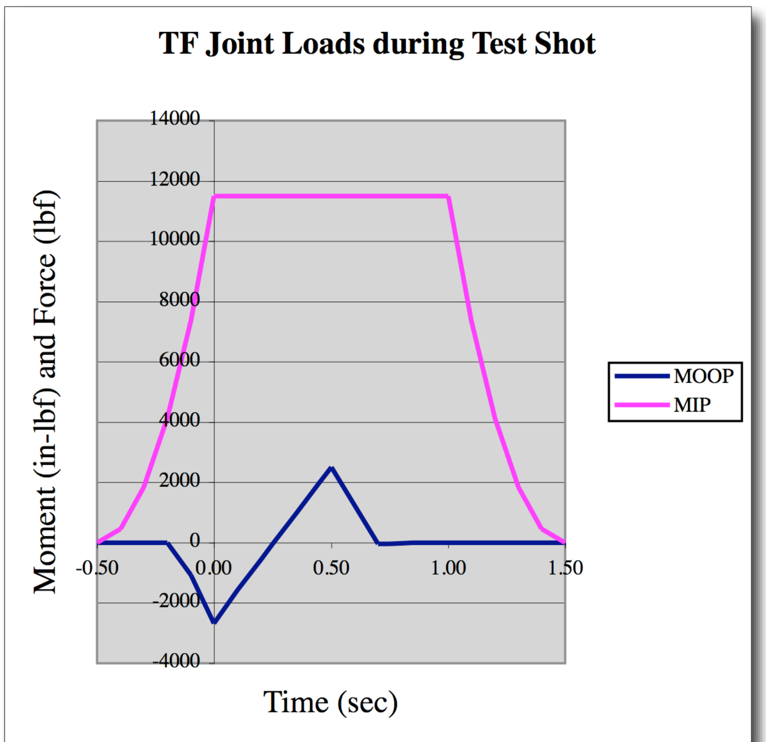
PF Current Range Consistent with Upcoming Plasma Operations

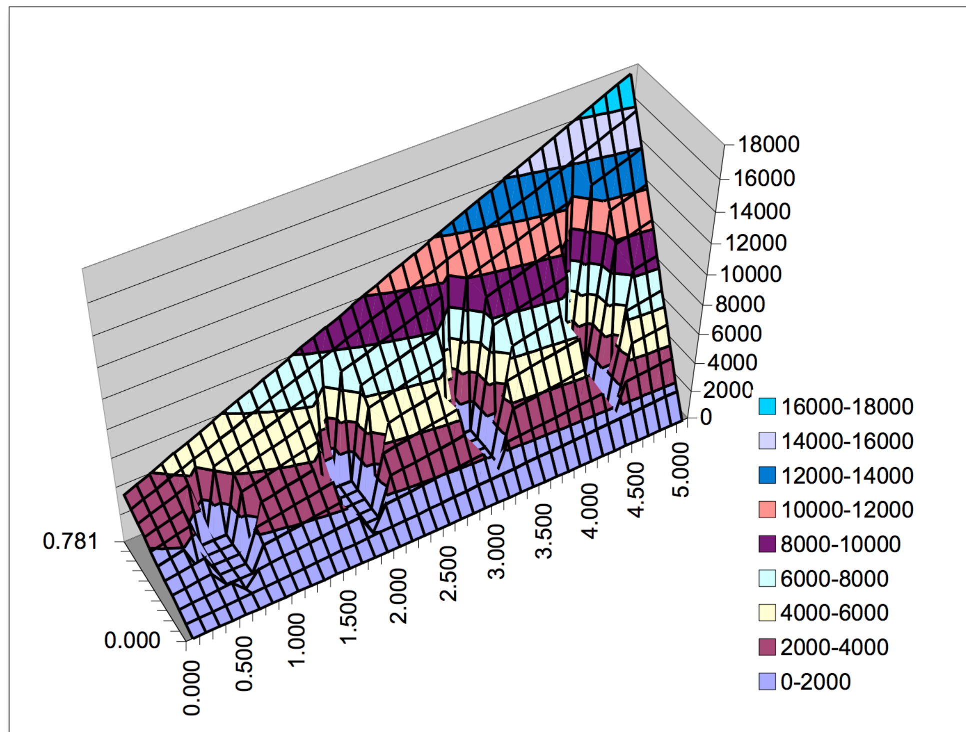
Target Operating Envelope - 4.5kG

Predicted joint performance…

✓M_ip ~ 11kin-lbf
✓M_oop ~ 2.7kin-lbf
✓minimal lift-off

✓P_max < 20ksi (excluding local peaks)
✓Box stud friction SF > 2
✓T_max < 150C





Target Operating Envelope - 6.0kG

- Bt ≤ 6.0kG

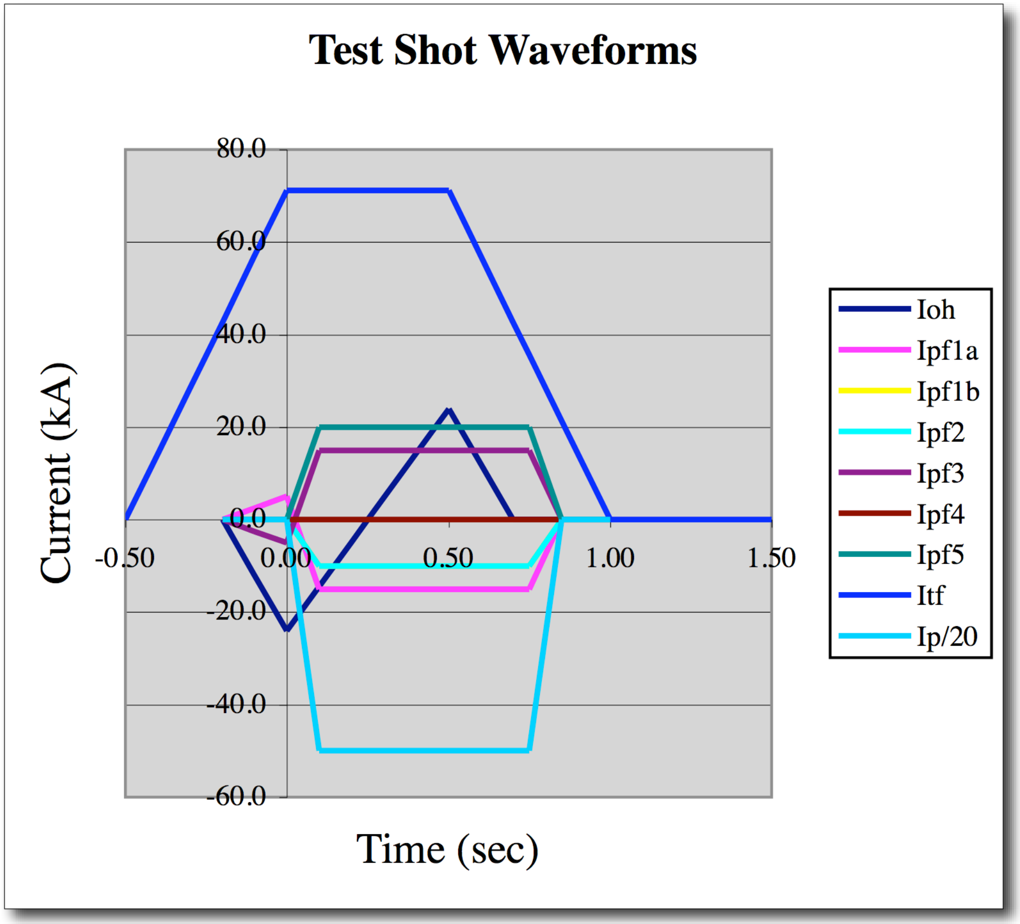
✓ 0.5 second flat top

✓ full OH (-/+24kA)

✓ other PF's…

  ✓|I_pf1a| ≤ 15kA
  ✓|I_pf1b| ≤ 10kA
  ✓|I_pf2| ≤ 10kA
  ✓|I_pf3| ≤ 15kA
  ✓|I_pf5| ≤ 20kA

✓ test shot waveform timing as indicated



PF Current Range Consistent with Upcoming Plasma Operations

Target Operating Envelope - 6.0kG

Predicted joint performance…

✓M_ip ~ 20kin-lbf
✓M_oop ~ 3.5kin-lbf
✓Liftoff to first bolt

✓P_max < 30ksi (excluding local peaks)
✓Box stud friction SF > 1.5
✓T_max < 150C