TF Joint Operations Review Simplified Modeling & Protection

- ✓IP and OOP Load Modeling
- ✓Linear Model of IP and OOP pressure at Joint
- ✓FEMLAB thermal/electrical simulation
- ✓Other limiting factors
- ✓Spreadsheet assessment of test shots
- ✓Hardware and Software Protection

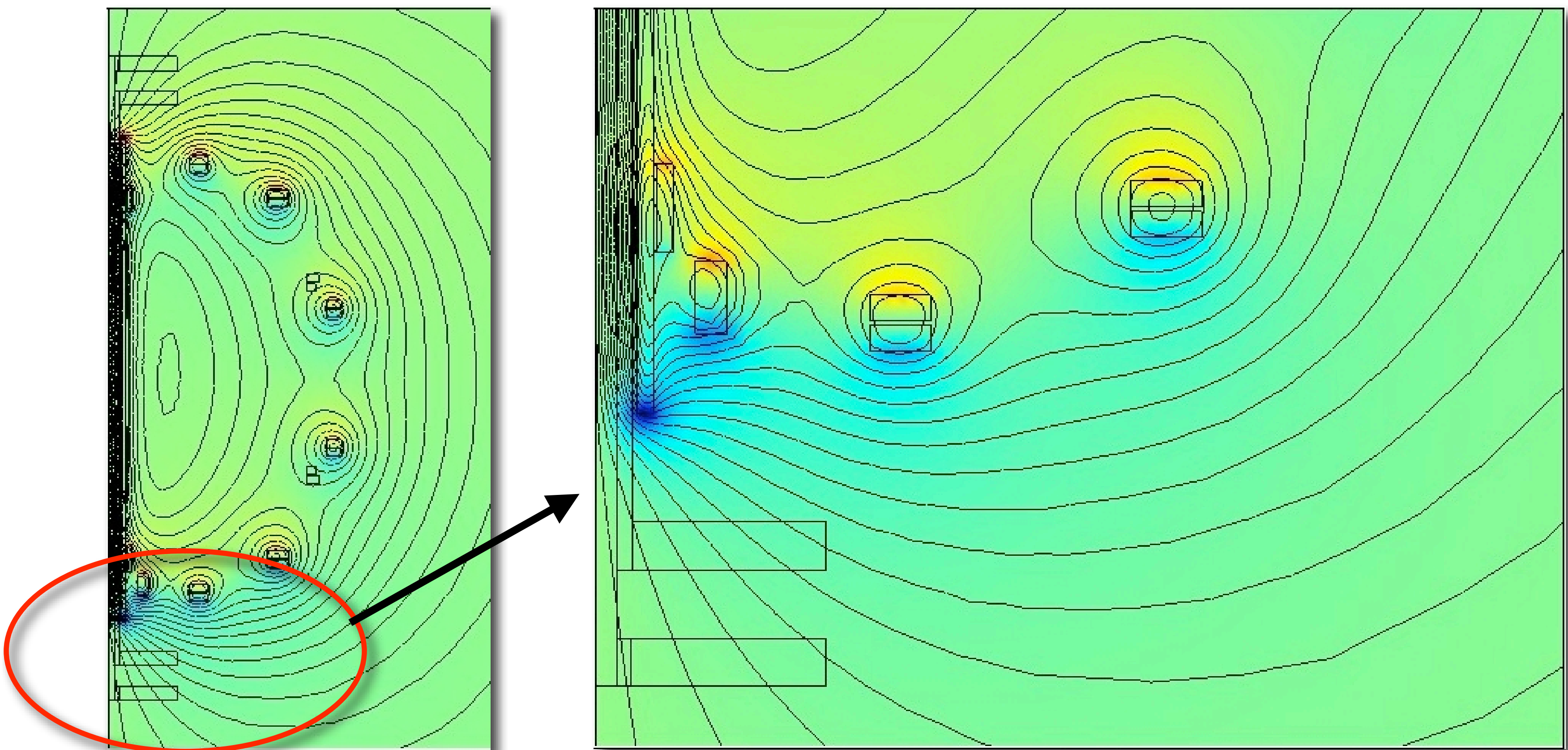
C Neumeyer

2/10/05

EM Influence Matrix

•FEMLAB was used to model the poloidal field using 2-d axi-symmetric magnetics mode

•Sub-domains were created to represent regions of the TF coil so J_tf x B_r and J_tf x B_z forces on TF bundle and flags could be calculated per kA in each OH/PF coil



EM Influence Matrix

TF Influence Coefficients (forces: lbf/kA^2, moments: lbf-in/kA^2, radii: inches)

Note: Moments taken about NSTX machine axis

	OH	PF1aU	PF1aL	PF1b	PF2U	PF2L	PF3U	PF3L	PF4U	PF4L	PF5U	PF5L
F_Inner	0.220	0.000	0.022	0.172	0.009	0.650	0.035	0.651	0.047	0.195	0.089	0.238
F_Outer	0.468	0.001	0.044	0.378	0.011	1.175	0.045	0.885	0.059	0.255	0.113	0.305
M_Inner	2.685	0.006	0.274	2.117	0.117	8.517	0.479	8.848	0.633	2.645	1.211	3.236
M_Outer	5.012	0.008	0.528	4.302	0.151	15.620	0.613	12.210	0.814	3.504	1.551	4.194
Reff_Inner	12.205	13.636	12.627	12.308	13.605	13.103	13.608	13.591	13.613	13.564	13.622	13.597
Reff_Outer	10.709	13.684	12.027	11.381	13.853	13.294	13.744	13.797	13.750	13.741	13.726	13.751
∑M_Bundle	-154.25	-0.015	-6.220	-8.596	-0.207	-0.769	-0.708	-1.416	-0.875	-1.639	-1.418	-2.099
∑M_Flag	207.400	-0.074	0.250	2.825	0.869	6.219	-2.623	2.415	-2.813	-1.622	-4.061	-2.889
∑M_Net	152.508	0.259	15.960	128.652	5.028	477.084	20.460	399.216	27.132	115.836	51.756	139.488

- z/z_{max} term is applied to the bundle moment calculation to approximate the amount of torsional load taken out at the hub end of the bundle as if it was a fixed boundary

- Note relative importance of OH on bundle torque and PF2/PF3 on flag lateral load and moment

Out-Of-Plane Moment

- Net moment on joint is estimated as follows…

✓Assume equal bundle torque taken out per each of the 36 flags

$$M_{joint\_bundle} = M_{bundle} / 36$$

✓Flag torque at joint based on lateral force and equivalent radius

$$M_{joint\_flag} = F_{bundle} * (r_{equiv} - r_{bundle})$$

✓Net moment at joint is sum of applied torques times coefficient reflecting load sharing with structure

$$M_{joint\_oop} = C_{s\_oop} * (M_{joint\_bundle} + M_{joint\_flag})$$

✓Structural coefficient C_s_oop derived from NASTRAN FEA, one per PF current (OH, PF1a ~ 25%, others ~ 10%)

In-Plane Moment

- Prior calculations show that moment generated on flag and flex link w.r.t. joint is 70653 in-lbf @ 6kG

✓Field and moment proportional to B_T^2

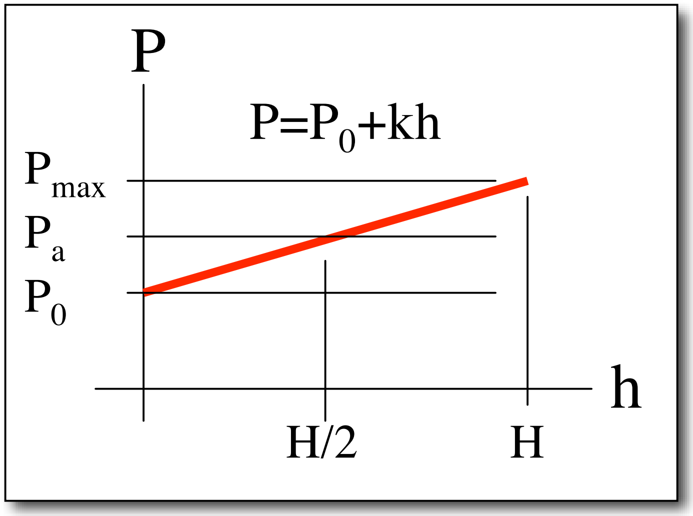
$$M = \left(\frac{B_T}{6}\right)^2 * 70653$$

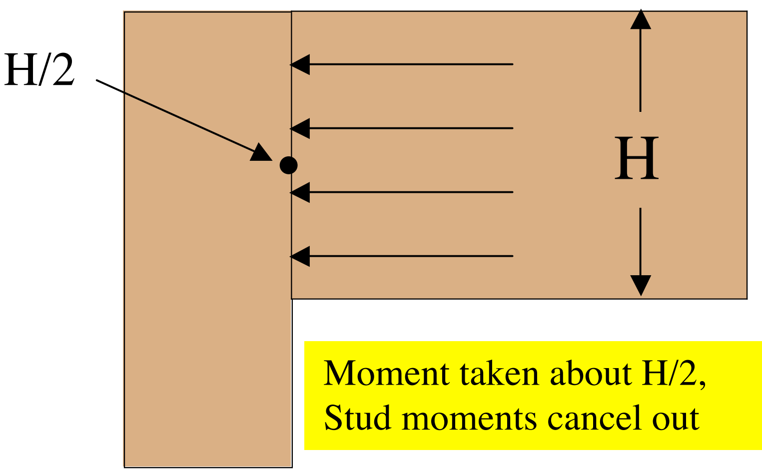
✓Net moment at joint is sum is applied moment times coefficient reflecting load sharing with structure

$$M_{joint\_ip} = C_{s\_ip}\left(\frac{B_T}{6}\right)^2 * 70653$$

✓Structural coefficient C_{s_ip} ~ 30% derived from NASTRAN FEA

Linear Pressure Model w/o Liftoff





$$F = \int P\,dA = w\int_0^H P\,dh = \frac{A}{H}\int_0^H (P_0 + kh)\,dh$$

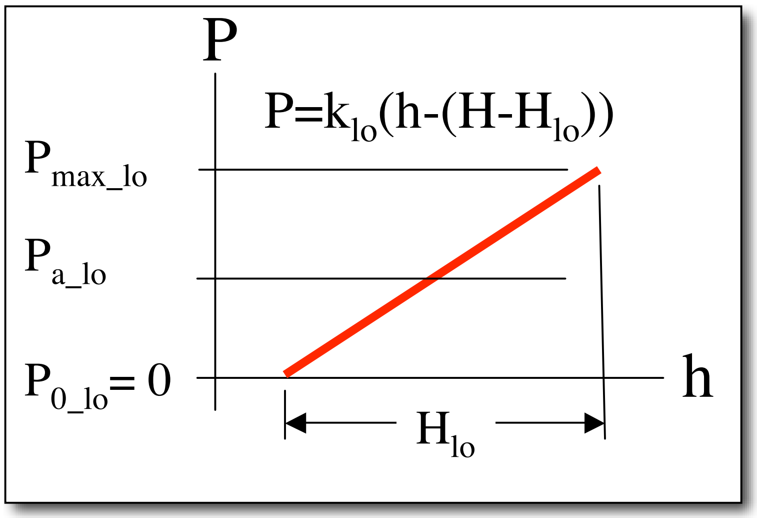
$$k = \frac{2(F - AP_0)}{AH} \qquad A = HW$$

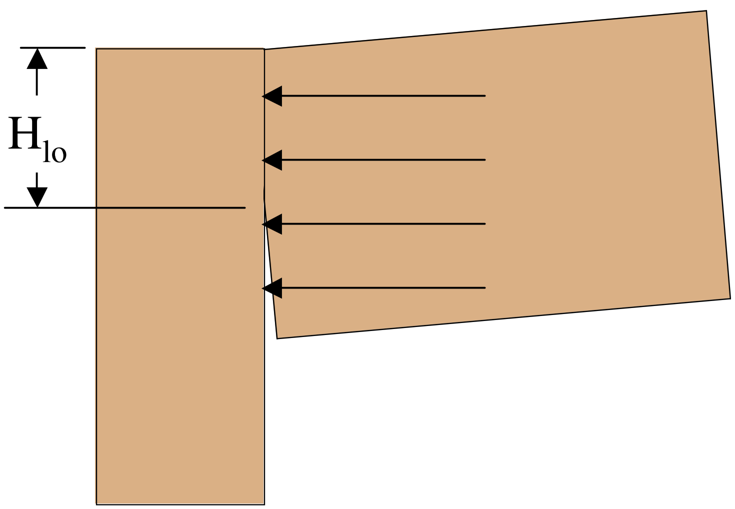
$$M = 2\int_0^{H/2} (P_a - P)(h - H/2)\,dA$$

$$P_0 = \frac{6M}{AH} - \frac{F}{A} \qquad P_{\max} = \frac{6M}{AH} + \frac{F}{A}$$

$$M_{liftoff} = \frac{FH}{6}$$

Linear Pressure Model w/Liftoff





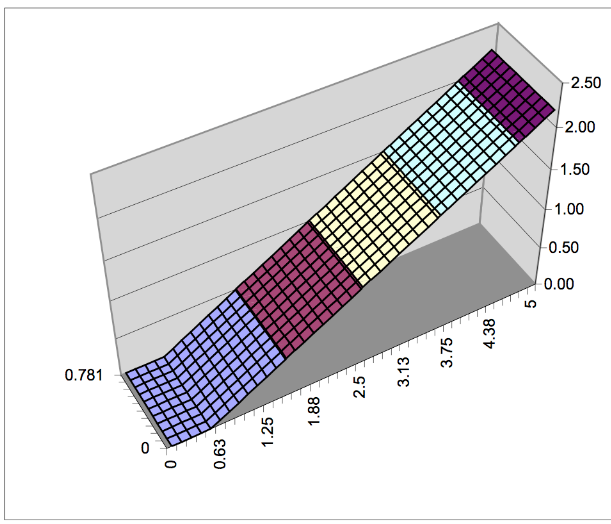
$$H_{lo} = \frac{H}{2} - \frac{3M}{F} \qquad P_{0\_lo} = 0$$

$$A_{lo} = H_{lo}W \qquad k_{lo} = \frac{2F}{A_{lo}H_{lo}}$$

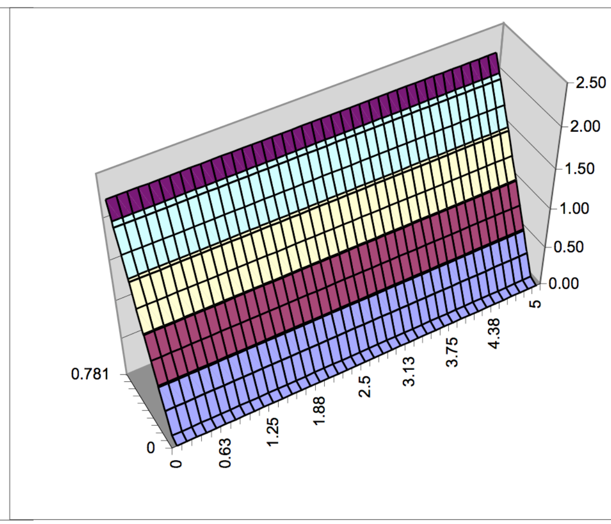
$$P_{max\_lo} = \frac{2F}{3W\left[\frac{H}{2} - \frac{M}{F}\right]}$$

Combined IP and OOP

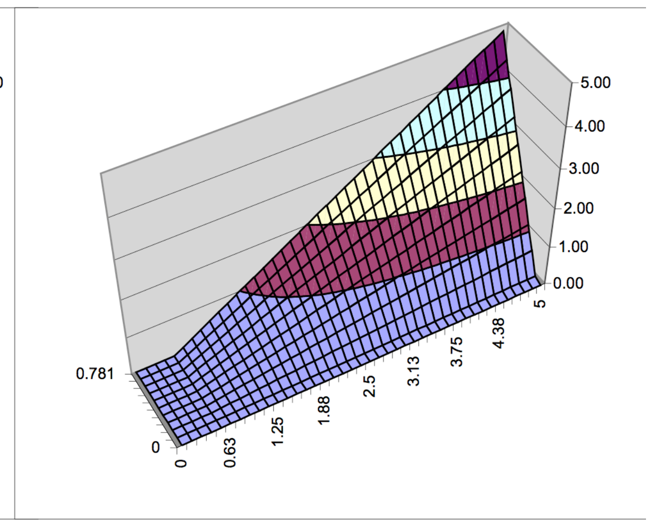
- Equations developed for IP apply to OOP with H and W reversed
- Assume superposition IP and OOP effects
- Question: how to estimate peak pressure considering effects of inserts, etc.



IP Only



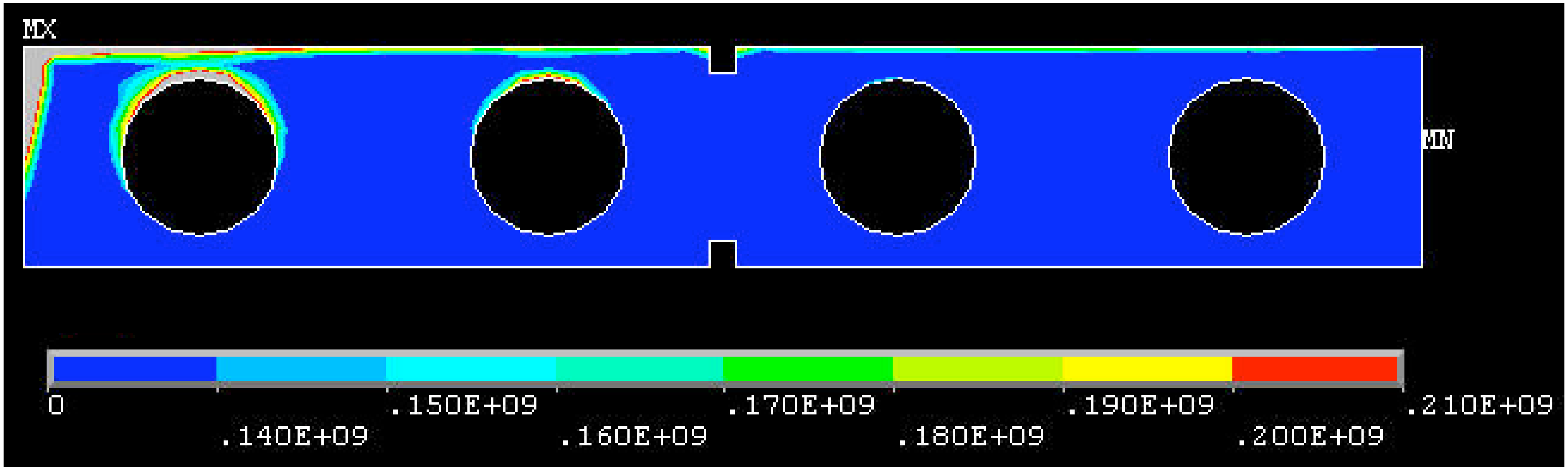
OOP Only

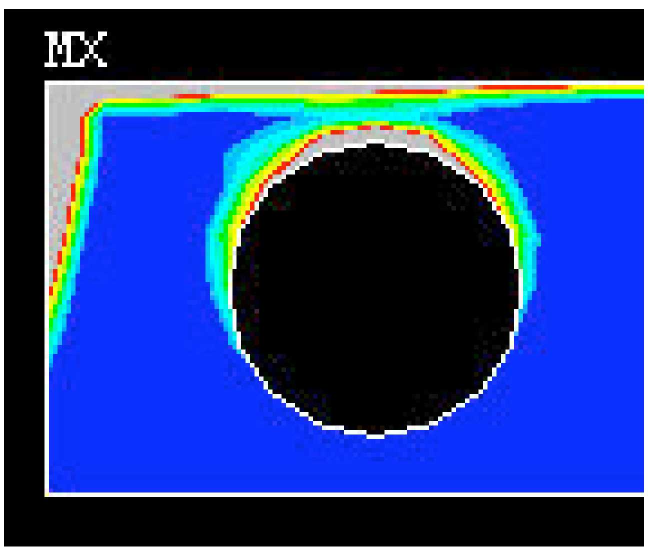


IP & OOP Combined

Pressure Peaking Factor

• 6kG moments ~ ANSYS case with M_ip = 20klbf-in and M_oop=3905





Red areas ~ 30ksi
Grey areas > 30ksi

Note: estimated worst case M_ip
During last run ~ 27klbf-in!!

Pressure Peaking Factor

• Linear model under same conditions as ANSYS run results in 30.5ksi based on gross average pressure

• How to handle non-uniformity in simplified model?

✓ Ignore peaking factor in model

✓ Set allowable for simple model based on knowledge of actual situation

• Judgement to be applied in setting allowable

✓ Peaking at corner is to some extent an artifice of the calculation
✓ Plastic deformation at corner is to some extent tolerable

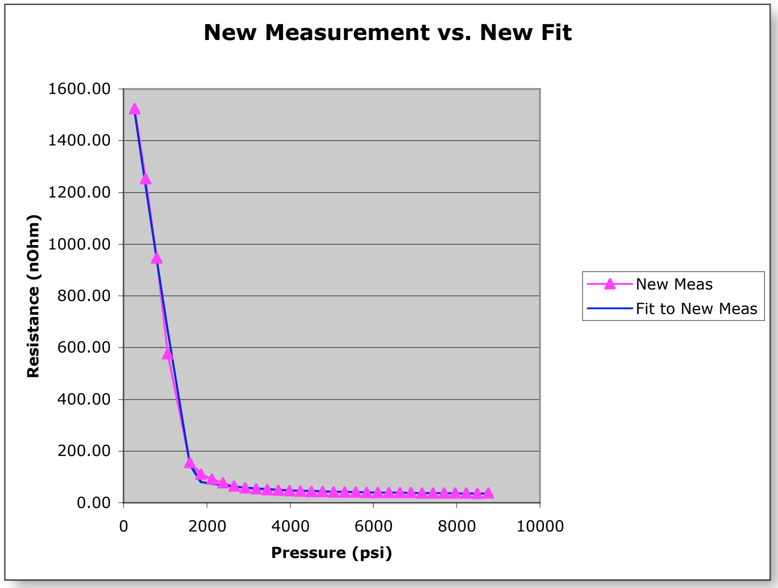
• Bundle conductor is C107 copper specified with yield strength 30 ksi min/36ksi max

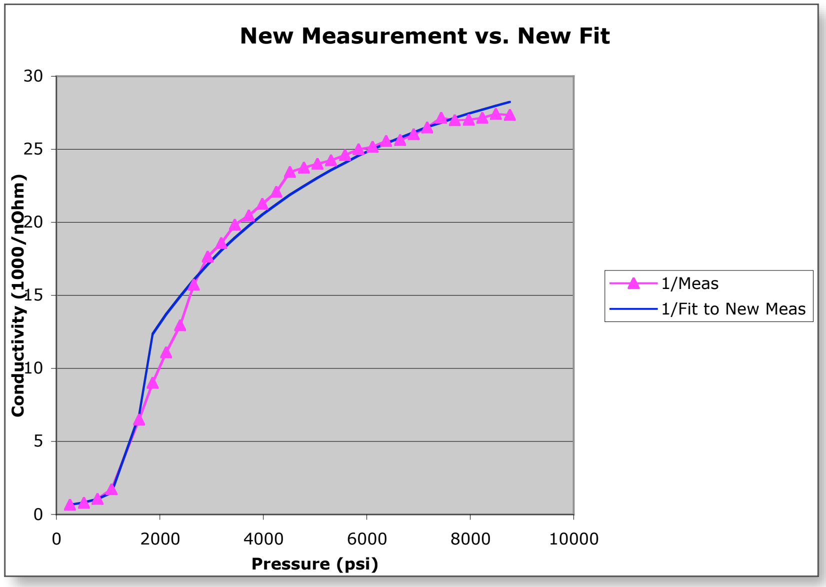
• Flag conductor is C101 copper

✓Tested Rockwell Hardness B = 45
✓H04 tensile yield ~ 40ksi per CDA specs

FEMLAB Modeling

- Linear pressure model
  - ✓In-plane moment set proportional to Itf^2
  - ✓Out-of-plane moment set proportional to Itf at OHSS value (conservative)
- Contact electrical resistivity based on curve fit to measurements on prototype assembly
- Contact thermal conductivity varied along with electrical conductivity
- Water cooling ignored





Fit: ρ = max(KA+KB*P, KC*P)^KD)

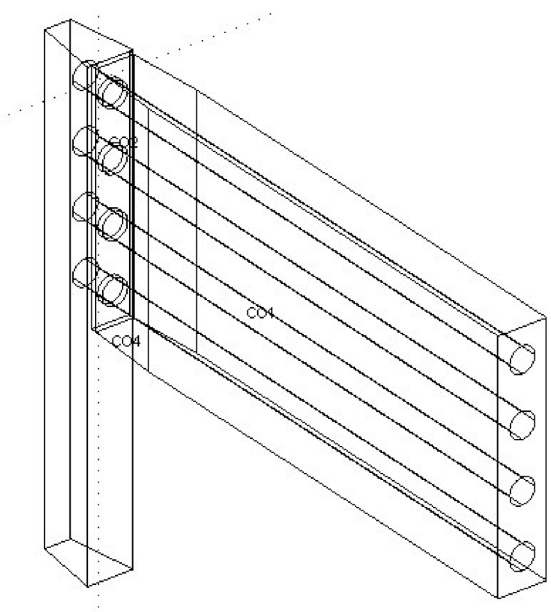
KA	7.336E+00
KB	-4.218E-03
KC	1.178E+03
KD	-1.102E+00

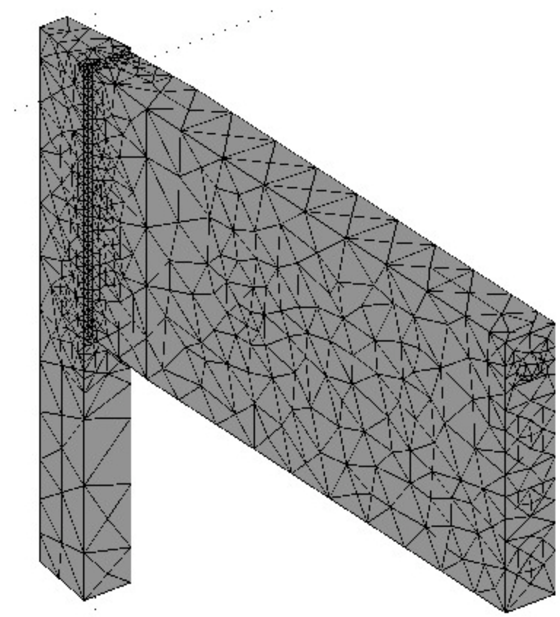
FEMLAB Meshing

• Contact region simulated using thin (0.125”) layer

- ✓ viable for FEA meshing
- ✓ presents correct impedance and power dissipation
- ✓ small thermal capacity
- ✓ stable temperatures
- ✓ temperatures in layer are an artifice of the calculation and are ignored

• Noted that primary effect of contact resistance is to steer the current flow, and that power dissipation is a secondary factor





8490 elements

FEMLAB Simulation - Front Face of Conductor

- Simulation (6kG shown) predicts Tmax ~ 155C in conductor in thin region near insert

FEMLAB Simulation - Front Face of Flag

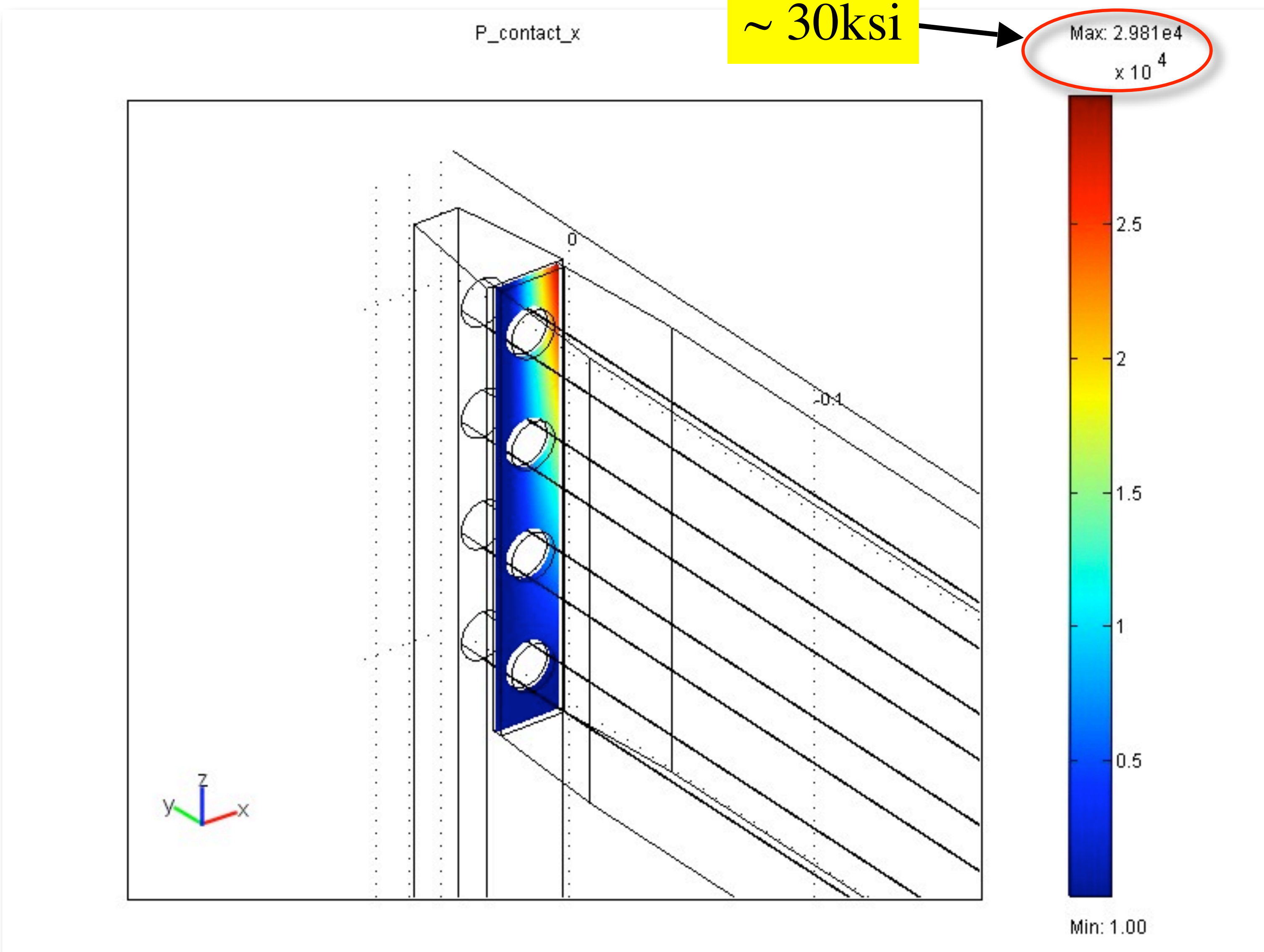
- Results are consistent with field measurements - flag heating mirrors conductor except where liftoff has occurred

FEMLAB Simulation - Back Side of Conductor

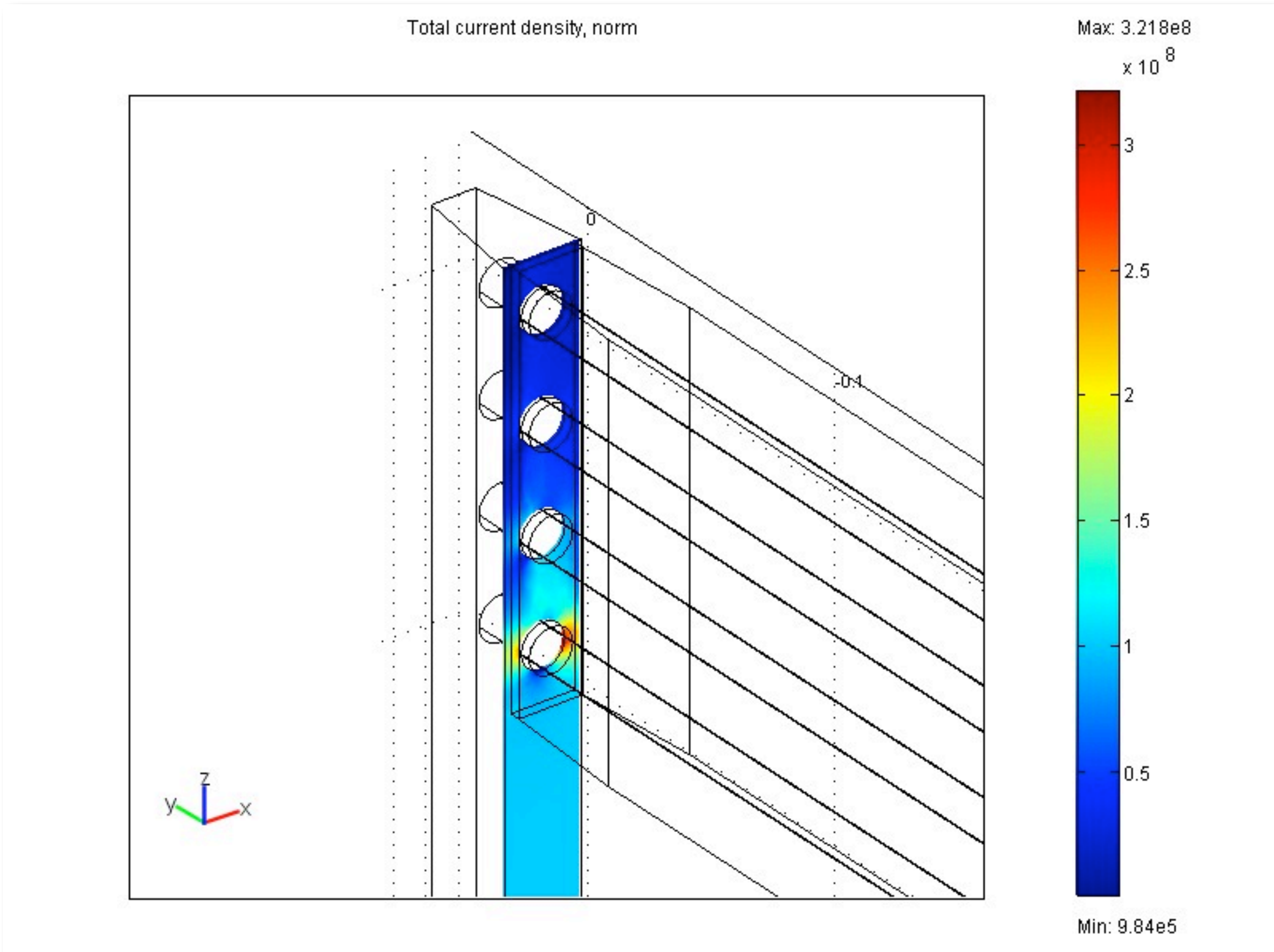
- Back side of conductor near water coolant passage well below 100C

FEMLAB Simulations - 6kG - Pressure (psi)

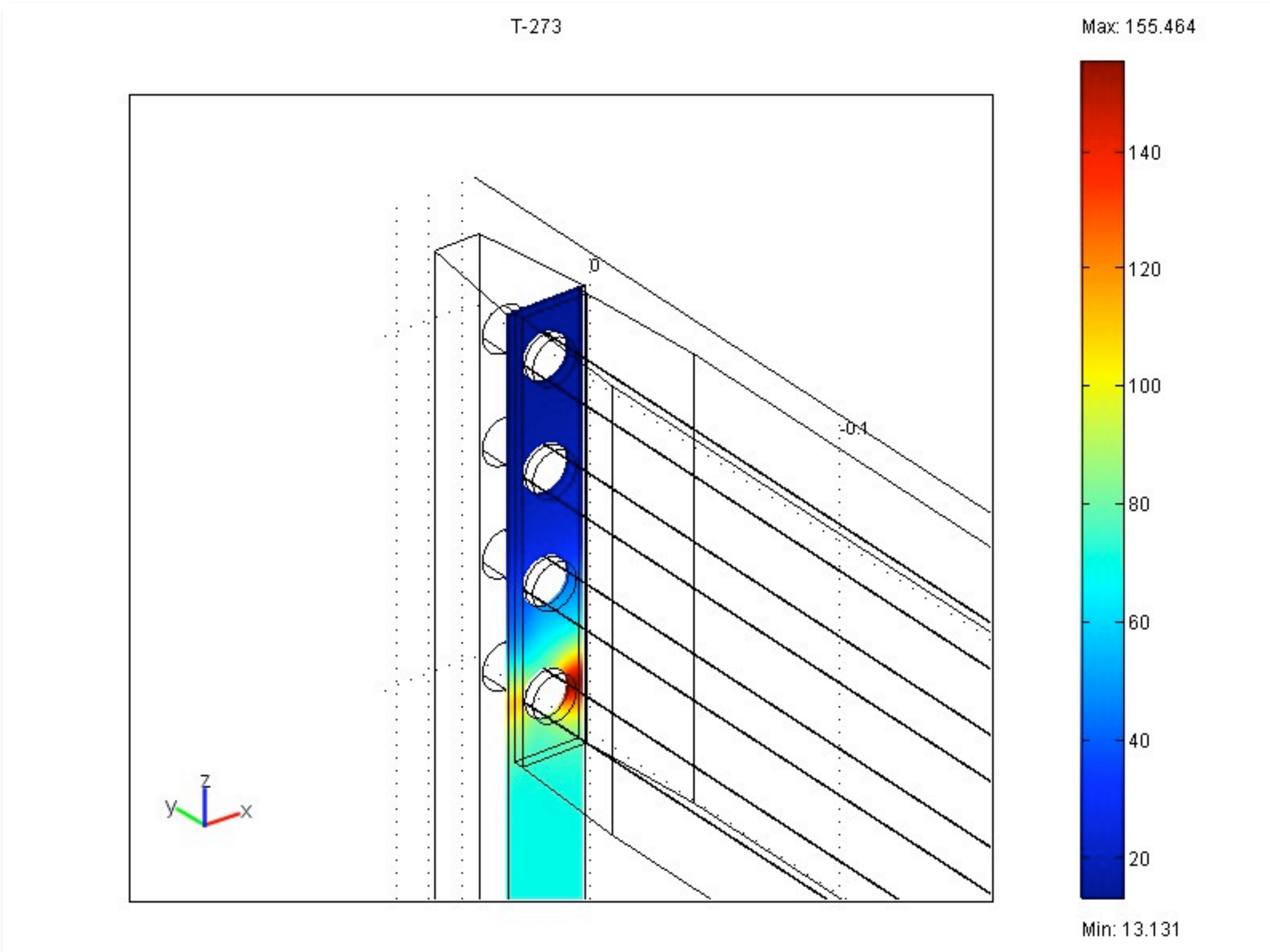
~ 30ksi



FEMLAB Simulations - 6kG - J (A/m^2)

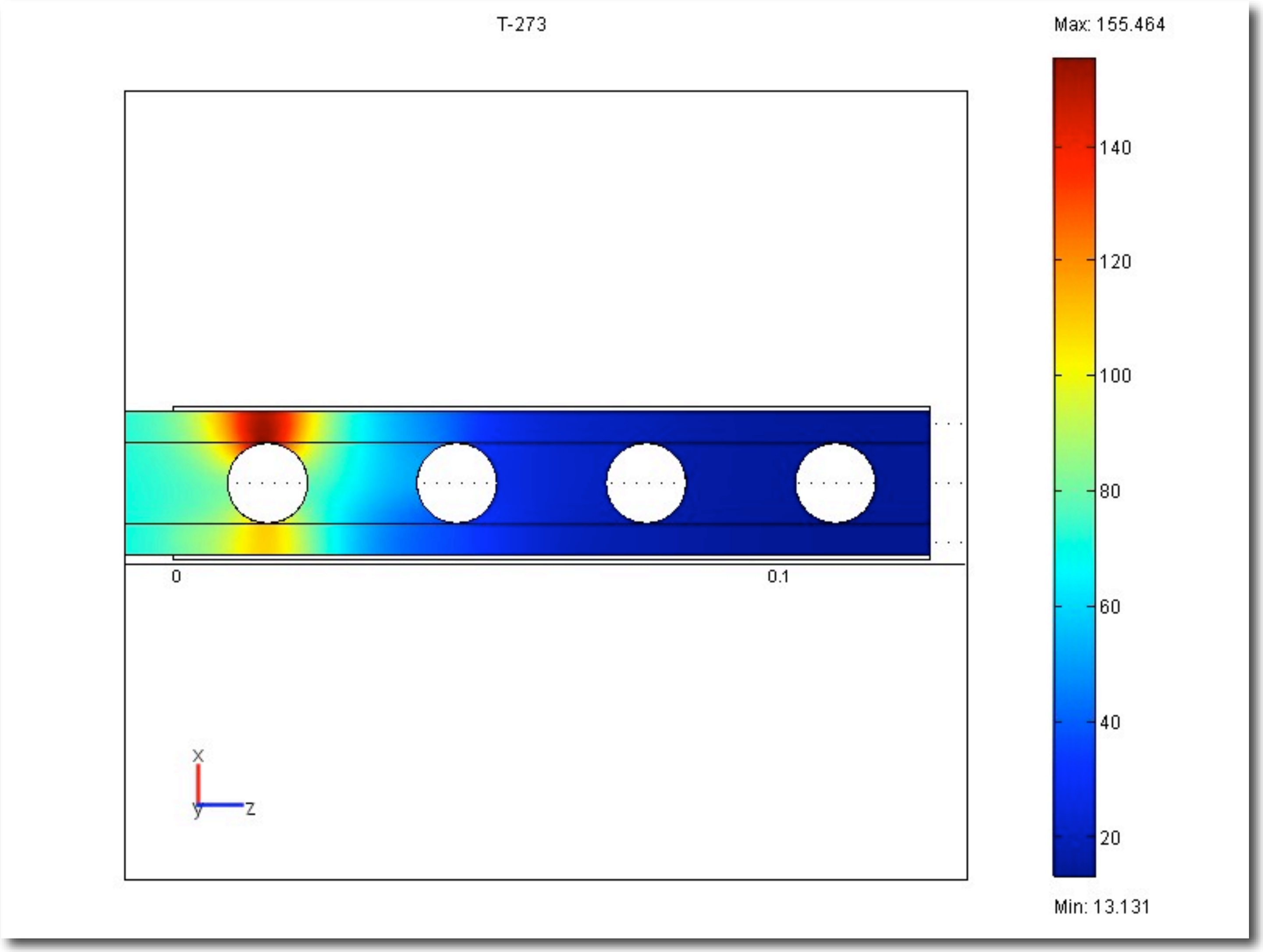


FEMLAB Simulations - 6kG - T (^{o}C)



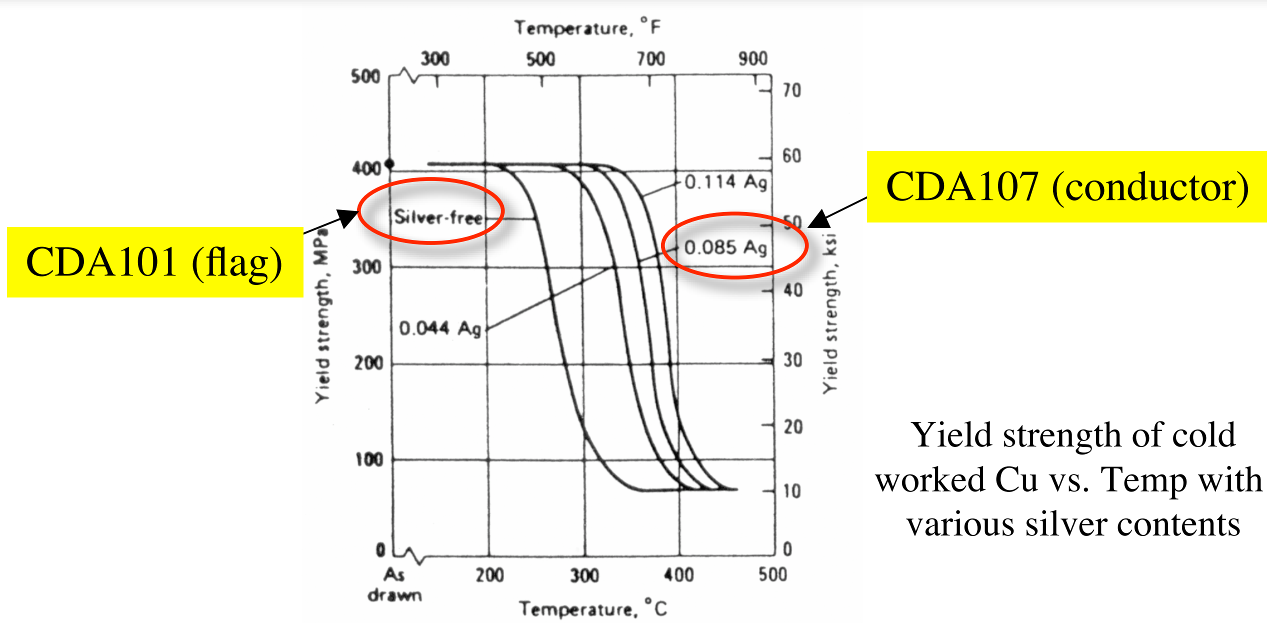
FEMLAB Simulations - 6kG - T (^{o}C)

Should be ~ worst case, since J and heating is aligned with insert



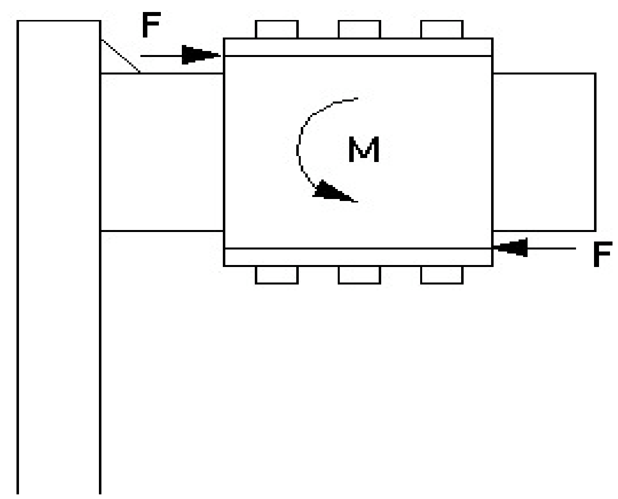
FEMLAB Simulations - Summary

- Copper mechanical properties do not degrade until ~ 200C (flag) and 300C (conductor)
- TF bundle insulation (near hot spot) pre-cured 2hrs at 177C and post-cured 7hrs at 200C
  - ✓Heat distortion temperature should be close to 200C
- Set temperature limit to 150C, corresponding to ~ 0.5s flat top @ 6kG worst case
  - ✓Water cooling region will remain below well below 100C
- Conclusion: I2T protection presently in place is adequate for thermal protection

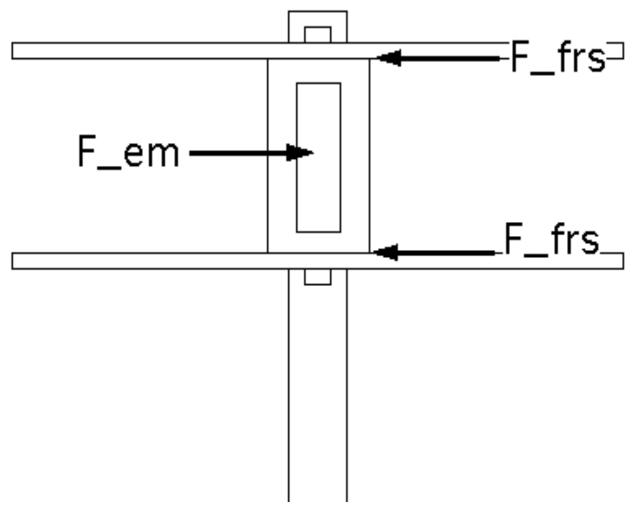


Yield strength of cold worked Cu vs. Temp with various silver contents

Other Limiting Factors - Box Friction



In-Plane



Out-Of-Plane

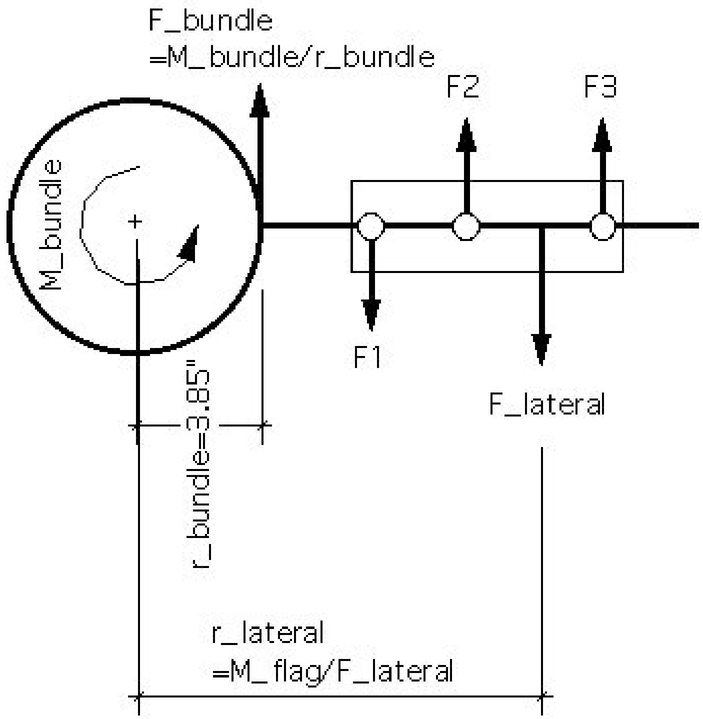
Box Friction - Out Of Plane

• Simplified model treats flag/box assembly as a simple rigid body statics problem, and friction response of the interface as point responses at the radii of the box studs

•$F_{lateral}$ from EM influence matrix

•F_{bundle} from influence matrix w/structural coefficient C_s (82%) from NASTRAN FEA

• Load response of flex links is ignored



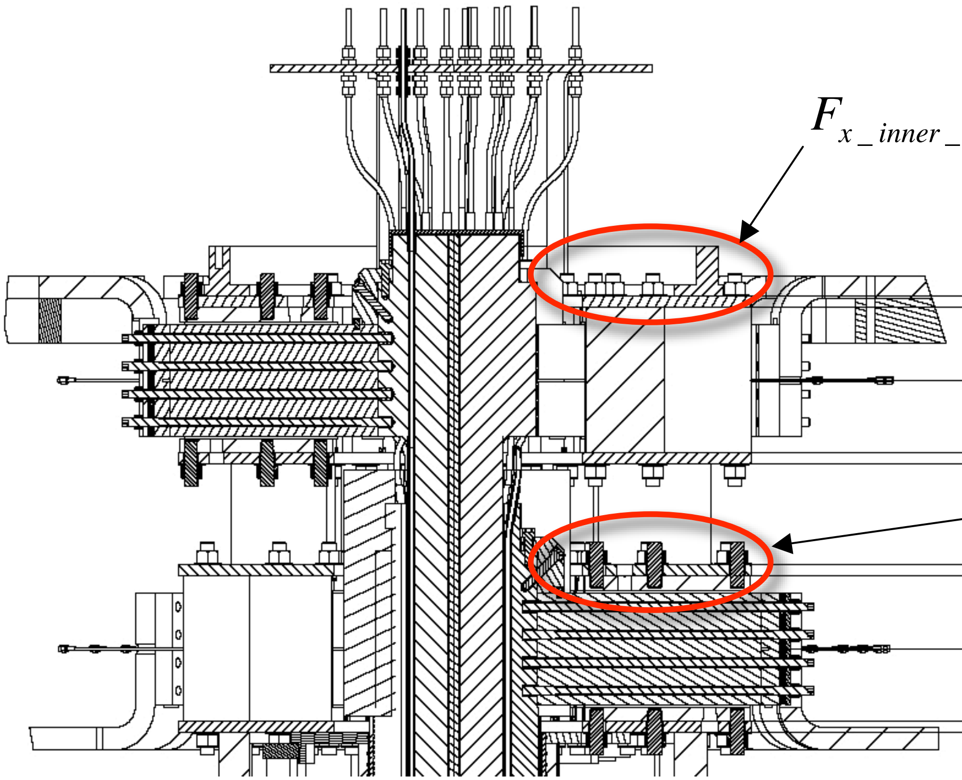
$$F_3 = \frac{\left[\frac{(F_b * r_b + F_l * r_l)(r_3 - r_1)}{(r_1(r_3 - r_1) + r_2(r_3 - r_2))} - \frac{(F_b + F_l)(r_3 - r_1)}{(2r_3 - r_1 - r_2)}\right]}{\left[\frac{(r_3 - 2 * r_1 + r_2)}{(2r_3 - r_1 - r_2)} - \frac{(r_3 * (r_3 - r_1) + r_2 * (r_2 - r_1))}{(r_1(r_3 - r_1) + r_2(r_3 - r_2))}\right]}$$

$$F_1 = \frac{-\left[F_3(r_3 - 2r_1 + r_2) + (F_b + F_l)(r_3 - r_1)\right]}{(2r_3 - r_1 - r_2)}$$

$$F_2 = F_1 - \frac{(F_1 - F_3)(r_2 - r_1)}{(r_3 - r_1)}$$

Box Friction - Out Of Plane

- Individual F_x assumed equally divided between the two friction surfaces
- Total lateral load $\Sigma F = F_1 + F_2 + F_3$ loads has to be transmitted by outer surface
- Inner layer boxes have to transmit ΣF loads generated on outer layer boxes



$$F_{x\_inner\_oop} = \frac{F_{x\_inner}}{2} + \frac{\sum F_{x\_inner}}{3} + \frac{\sum F_{x\_outer}}{3}$$

$$F_{x\_outer\_oop} = \frac{F_{x\_outer}}{2} + \frac{\sum F_{x\_outer}}{3}$$

Box Friction - In Plane

• Moment generated on flag and flex link w.r.t. joint is 70653 in-lbf @ 6kG

✓Field proportional to Bt^2 at lower fields

$$M = \left(\frac{B_T}{6}\right)^2 * 70653$$

• Net friction shear at interface based on applied moment, moment arm, 2 interfaces, 3 studs per interface, and coefficient C_s reflecting load sharing with structure

$$Fs\_ip = \frac{C_s M}{(2*3)\left(\frac{\Delta z_{box}}{2}\right)}$$

✓Structural coefficient C_s_ip (28%) derived from NASTRAN FEA

Box Friction - Net

- Net friction shear load for each stud taken as vector sum of IP and OOP loads
- COF = 0.47 based on full scale tests on friction coated samples
- Stud loads taken to be 5500lbf based on average of torque vs. load tests
- Safety factor calculated for each of 3 studs on inner and outer flags, surfaces furthest away from midplane
- SF = 1 corresponds to a load of 0.47*5500=2585 lbf per stud

Joint Friction - Out of Plane

• Torque generated in TF bundle has to be reacted in frictional shear at joints

• Total bundle torque estimated using EM influence matrix with structural coefficient from NASTRAN FEA

• Total of 36 joints at 20klbf with COF = 0.2 for Ag plated copper (min R&D value)

• Safety factor based on total friction capability divided by total bundle torque (assumes equal load per turn)

Spreadsheet Assessment of Test Shots

- Test shots designed to simulate plasma ops envelope in terms of current magnitudes, polarities, and time dependence, used during commissioning and daily start up

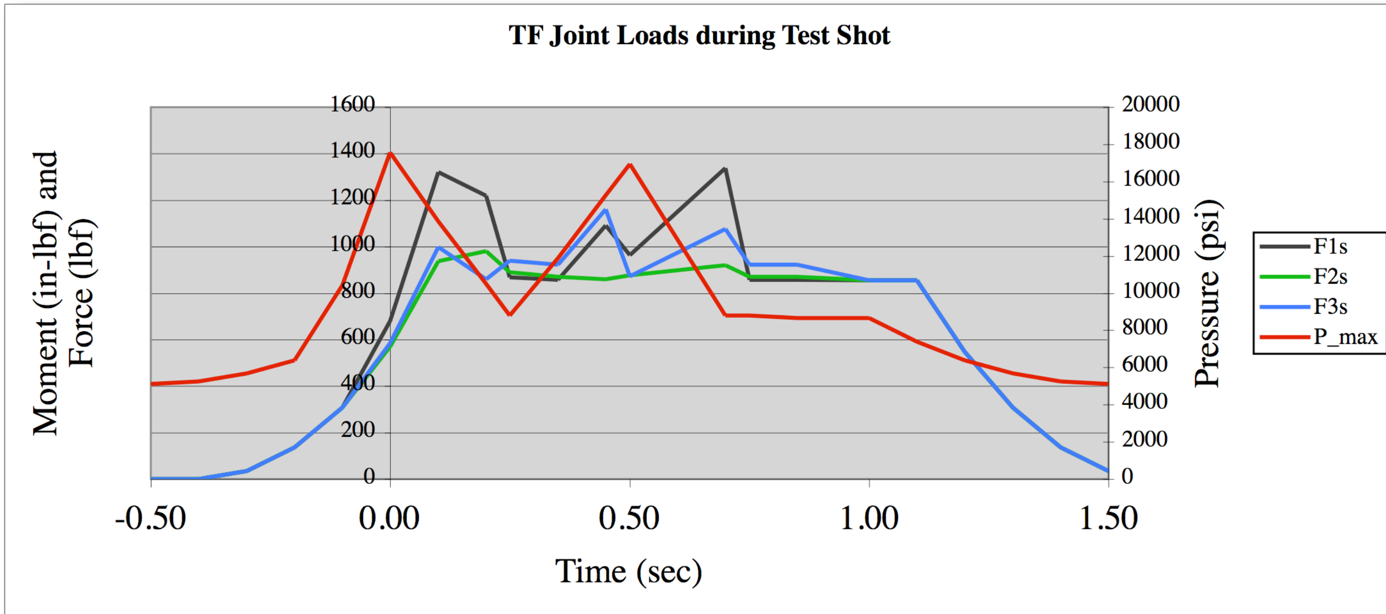
- Magnitudes selected will support upcoming run based on input from physics ops

- Loss of control could theoretically result in all currents aligned to the max magnitude in either direction, as limited by software and hardware protection

Test Shot Spec / Limit Spec

	Bt	4.5									
	T_flat	1.0				Rated		Rated	Rated	Req'd	Req'd
CASE	TF_SOFT	PF_SOFT	OHZC	OHSS	PF_EOFT	MAX_P	MIN_N	Max	Min	Max	Min
Ioh	-24.0	-16.0	0.0	24.00	0.0	24.0	-24.0	24.0	-24.0	24.0	-24.0
Ipf1a	5.0	-15.0	-15.0	-15.0	-15.0	5.0	-24.0	5.0	-24.0	5.0	-15.0
Ipf1b	0.0	-10.0	-10.0	-10.0	-10.0	0.0	-20.0	0.0	-20.0	0.0	-10.0
Ipf2	0.0	-10.0	-10.0	-10.0	-10.0	20.0	-20.0	20.0	-20.0	0.0	-10.0
Ipf3	-5.0	15.0	15.0	15.0	15.0	20.0	-20.0	20.0	-20.0	15.0	-5.0
Ipf4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ipf5	0.0	20.0	20.0	20.0	20.0	20.0	0.0	20.0	0.0	20.0	0.0
Itf	53.4	53.4	53.4	53.4	53.4	53.4	53.4	53.4	53.4	53.4	53.4

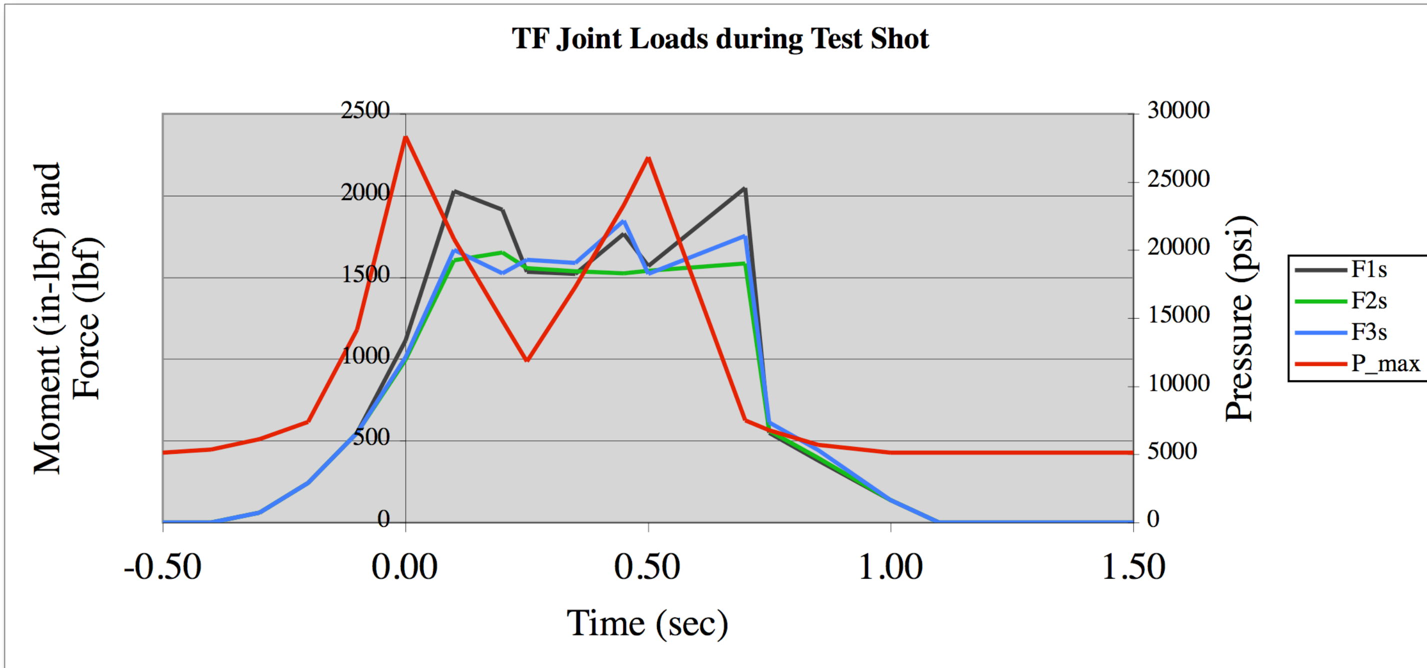
Spreadsheet Assessment - 4.5kG



	TF_SOFT	PF_SOFT	OHZC	OHSS	PF_EOFT	Req'd MAX_P	Req'd MIN_N	Rated MAX_P	Rated MIN_N	
M_Joint_Outer_IP	11490	11490	11490	11490	11490	11490	11490	11490	11490	in-lbf
M_Joint_Outer_OOP	2679	1570	45	2497	45	3420	3601	4512	4960	in-lbf
Liftoff	Liftoff					Liftoff	Liftoff	Liftoff	Liftoff	
P_max_Joint_Outer	17.6	13.9	8.8	17.0	8.8	20.5	21.4	27.3	31.6	ksi
Min Box Bolt Friction SF Outer	2.7	3.4	3.9	2.6	3.9	1.8	1.9	1.0	1.0	
Min Box Bolt Friction SF Inner	3.4	5.5	6.8	3.4	6.8	1.9	2.1	1.0	1.1	
Flag Friction OOP SF	3.5	5.5	146.1	3.5	146.1	3.3	3.3	3.3	3.1	

- All factors are OK with limits at “Req’d”
- Pressure > 30ksi and Box Stud SF ~1 are possible with limits set to “Rated”

Spreadsheet Assessment - 6.0kG



	TF_SOFT	PF_SOFT	OHZC	OHSS	PF_EOFT	Req'd MAX_P	Req'd MIN_N	Rated MAX_P	Rated MIN_N	
M_Joint_Outer_IP	20427	20427	20427	20427	20427	20427	20427	20427	20427	in-lbf
M_Joint_Outer_OOP	3572	2093	59	3330	59	4560	4802	6016	6614	in-lbf
Liftoff	Liftoff	Liftoff	Liftoff	Liftoff	Liftoff	Liftoff	Liftoff	Liftoff	Liftoff	
P_max_Joint_Outer	28.4	20.8	11.8	26.8	11.8	37.0	40.0	67.0	100.5	ksi
Min Box Bolt Friction SF Outer	1.8	2.1	2.3	1.8	2.3	1.3	1.4	0.7	0.7	
Min Box Bolt Friction SF Inner	2.5	4.1	4.6	2.6	4.6	1.4	1.6	0.8	0.8	
Flag Friction OOP SF	2.6	4.1	109.6	2.6	109.6	2.5	2.4	2.5	2.3	

- Pressures >> 30ksi are possible in “Req’d” and “Rated” cases
- Box stud friction SF < 1 in “Rated”
- Flag OOP friction SF OK in all cases

Spreadsheet Assessment - Comparison w/NASTRAN

RUN CASE	M_IP_NASTRAN	M_IP_Model	M_OOP_NASTRAN	M_OOP_Model
4.5 kG – EOFT – 100% = No PF – Run 48N	10340	11490	13	0
4.5 kG – SOFT – 24 kA OH, only – Run 72N	10810	11490	2542	2542
4.5 kG – SOFT – 5 kA PF3, only – Run 73N	6670	11490	170	170
4.5 kG – SOFT – 5kA PF1A, only – Run 74N	11460	11490	33	33
4.5 kG – SOFT – 10 kA PF2, only – Run 77N	11390	11490	461	461
4.5 kG – SOFT – 20 kA PF5, only – Run 78N	11360	11490	336	336
4.5 kG – SOFT – No PF – Run 47NA	11490	11490	0	0
4.5 kG – SOFT – 100% PF – Run 70N	10920	11490	2667	2679
4.5 kG – OHSS – 100% PF – Run 71N	10430	11490	2827	2827
6.0 kG – SOFT – 100% PF – Run 75N	17770	20427	3390	3572
6.0 kG – OHSS/EOFT – 100% PF – Run 76N	10340	20427	3424	3769

Combined field

- OOP Combined field cases add up pretty well at 4.5kG and 6kG
- IP is overestimated at 6kG, particulary for combined field
- Modeled P_max would be reduced to 20ksi from 28ksi if M_ip was 10340 at 6kG

Spreadsheet Assessment - Conclusions

•At 4.5kG

✓*According to modeling results* overcurrent limits set per present *requirements* are adequate, and exposure to problems will be minimal

•At 6kG

✓*According to modeling results* nominal waveforms are feasible, with liftoff and local yielding.

✓Moments at the joint will be less than were experienced by worst case joints during prior run at 4.5kG

✓Real time protection against P_max overloads is necessary even if currents are limited in magnitude to *required* values

Spreadsheet Assessment - Conclusions

• Simplified linear modeling provides results which are reasonably close to detailed analysis and are suitable for real time protection accounting for PF current combinations

• Real time protection is required to prevent P_max and box friction overloads *if/when PF operating levels are increased over present requirements, and/or when Bt is operated above 4.5kG*

• Protection of box friction based on the most inboard stud will blanket worst case conditions

• OOP joint friction retains adequate margins in all cases

Hardware and Software Protection

• Overcurrent Protection

- Analog Coil Protection (ACP) and Rochester Instrument System (RIS) and Power Supply Real Time Control (PSRTC) protection will continue to be set based on *required* currents, less than or equal to *rated* currents

  ✓ PSRTC at 1% overcurrent
  ✓ ACP at 2% overcurrent
  ✓ RIS at 5% overcurrent

Hardware and Software Protection

- I2T Protection

  -Prior PSRTC and RIS settings were based on 1 second flat top at 4.5kG, would allow ~ 250mS at 6kG

  - Settings will have to be increased to allow 0.5 sec at 6kG

Range of prior run
And initial range of
Upcoming run

		T_max_fault =72C	T_max_fault =88C
		I2T_trip = 3.5e9A^2-s	I2T_trip = 4.75e9A^2-s
Btf (kG)	Itf (A)	Tflat(s)	Tflat(s)
6	71160	0.254	0.500
5.5	65230	0.490	0.782
5	59300	0.730	1.084
4.5	53370	1.012	1.449
4	47440	1.377	1.930
3.5	41510	1.884	2.607
3	35580	2.644	3.628

Hardware and Software Protection

• Protection for TF joint (pressure, box stud load) will be implemented in PSRTC prior to operation beyond 4.5kG

• Although a "software" system, PSRTC software is segregated from and is more stable than the Plasma Control System (PCS)

• PSRTC will prevent any misoperations due to operator error or PCS malfunction