13-001212-CLN-01

TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: TF OPERATION AT 4.5kG WITH WATER COOLING ABSENT FROM TURN 6A

References

[1] 13-001206-CLN-02, "TF Limits vs. Temperature"
[2] 13-001206-PJH-01, "Results of Cooling and Shear Stress Analysis for NSTX TF Center Stack with No Active Cooling on Turn Six and Resulting Operational Limitations"
[3] 13-001208-HMF-01, "Stress Analysis of Loss of Coolant on Cool Down of TF Coil Inner Leg"

Present TF operational limits were set in ref. [1] based on a prospective adiabatic ΔT of 20C in the TF inner legs, which would lead to a 0.7*20C = 14C ΔT between turn 6A and the other turns of the bundle during cooldown. According to projections made at that time this would cause a shear stress of 1400 psi in the turn insulation, which would be 48% of the ultimate shear strength of 2942 psi assumed at that time.

Since then the follow-on work in ref. [2] and ref. [3] has shown that:

- indeed at a ΔT of 20C between turns the insulation shear stress is of order 2ksi (actual max. value projected to be 2.07ksi);
- shear strength, even at zero compression, is considerably larger (5883 psi) than that assumed earlier (2942 psi).

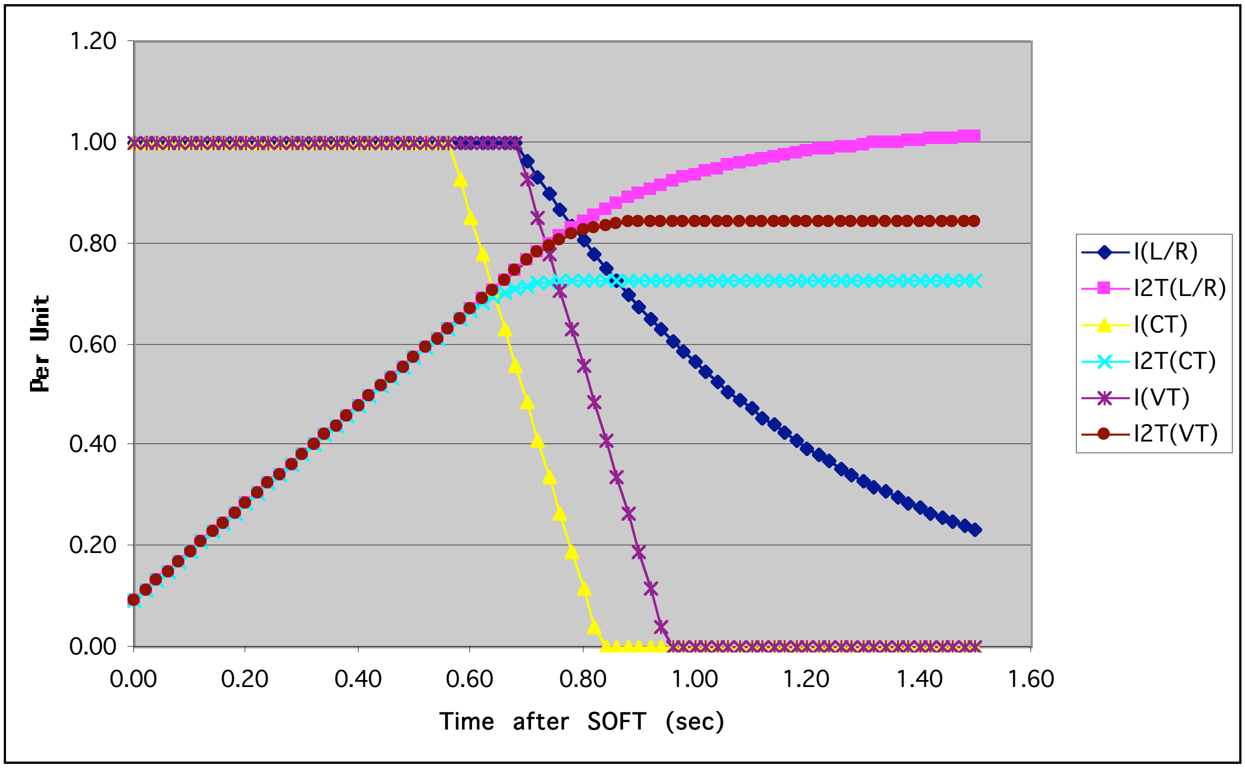
The above findings, along with the possibility of resurrecting the Rochester Instrument System (RIS) "1/2LI^2" module, improve the prospects for operating at 4.5kG under the present conditions.

The 1/2LI^2 module introduces a variability into the RIS trip setting which continuously anticipates the additional I2T which would be deposited into the coil should an L/R decay occur from the current at that moment (the equivalent square wave (ESW) of an L/R decay from an initial current I_o is $I_o^{2*}\tau$/2, where τ = L/R and is adjustable on the module). This feature allows an extension of the available flat top from that otherwise available according to the following logic:

Without the feature, the trip setting $I2T_{trip}$ is chosen such that, in case of a trip at full current, the final value of I2T will not exceed the maximum allowable $I2T_{max}$. Then in order to avoid trips on each shot, the end of flat top (EOFT) I2T is limited such that, after the current is ramped down, the additional $I2T_{ramp}$ added to the prior accumulation of I2T will not exceed the trip value, i.e. $I2T_{EOFT} + I2T_{ramp} < I2T_{trip}$.

With the feature, the trip point varies with current, increasing as the current decreases according to $I2T'_{trip} = I2T_{max} - I_o^{2*}\tau$/2.

The effect of the module is illustrated in the following feature which depicts the per unit TF current and I2T for three cases, namely 1) L/R decay at EOFT after I2T reaches $I2T_{trip}$, which ultimately deposits $I2T_{max}$ = 1.0 p.u. into the coil, 2) Ramp down of current at EOFT such that the at the completion of ramp down the total I2T is equal to a constant trip (CT) $I2T_{trip}$ and therefore no trip occurs, and 3) Ramp down of current at EOFT such that the variable trip (VT) $I2T'_{trip}$ is never exceeded and no trip occurs. It is evident from this figure, which was run for the 4.5kG case, that an additional ≈ 100mS of flat top can be gained.



The following table summarizes the options, assuming that we want ≈ 500mS flat top at 4.5kG:

	3.5kG w/o RIS Module	3.5kG w/RIS module	4.5kG w/o RIS module	4.5kG w/RIS Module
Max Flat Top Time (ms)	595	663	505	497
Fault Condition……				
ΔT Adiabatic (degC)	20	20	33	30
ΔT Turn-Turn (degC)	14	14	23.1	21
Shear (psi)	1449	1449	2390.85	2173.5
Shear (%Ultimate)	24.6%	24.6%	40.6%	36.9%
No-fault Condition……				
ΔT Adiabatic (degC)	14.3	14.3	23.4	23.1
ΔT Turn-Turn (degC)	10.01	10.01	16.38	16.17
Shear (psi)	1036	1036	1695	1673

Shear (%Ultimate)	17.6%	17.6%	28.8%	28.4%

It appears that an increase to 4.5kG, 500mS flat top time is feasible without substantial increase in risk from the insulation shear perspective. The incorporation of the extra RIS module would slightly reduce the exposure to temperature and stress but probably not enough to justify the cost and effort of implementation.

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Allowable Adiabatic ΔT	20	deg C
T0	12	deg C
G0	2.53E+15	(A/m^2)^2-sec
Tmax	32	deg C
Gmax	6.47E+15	(A/m^2)^2-sec
ΔGmax=J2Tmax	3.93E+15	(A/m^2)^2-sec
L	4.37E-03	Henry
Rcircuit (cold)	7.81E-03	Ohm
Rcircuit (hot)	8.19E-03	Ohm
Rpsequiv	4.03E-03	Ohm
∑R (cold)	1.18E-02	Ohm
∑R (hot)	1.22E-02	Ohm
CSA inner leg	6.74E-04	m^2
Bt	3.5	kG
Iflat	4.15E+04	Amp
J2T L/R decay	1.06E+15	(A/m^2)^2-sec
J2T Trip (RIS)	2.87E+15	(A/m^2)^2-sec
I2T Trip (RIS)	1.31E+09	A^2-sec
Trise	0.245	sec
J2T Rise	3.62E+14	(A/m^2)^2-sec
Tfall	0.202	sec
J2T Fall	2.55E+14	(A/m^2)^2-sec
J2T Flat	2.26E+15	(A/m^2)^2-sec
Tflat	0.595	sec
Gfinal	5.41E+15	(A/m^2)^2-sec
Tfinal	26.3	deg C
ΔTfinal	14.3	deg C
Gfinal (fault)	6.47E+15	(A/m^2)^2-sec
Tfinal (fault)	31.8	deg C

Bt	Iflat	Trise	Tfall	Tflat	∑T	Tfinal	ΔT
(kG)	(Amp)	(sec)	(sec)	(sec)	(sec)	(deg C)	(deg C)
3.0	35580.00	0.198	0.179	0.897	1.274	26.3	14.3
3.1	36766.00	0.207	0.184	0.826	1.217	26.3	14.3
3.2	37952.00	0.216	0.188	0.761	1.166	26.3	14.3
3.3	39138.00	0.225	0.193	0.702	1.120	26.3	14.3
3.4	40324.00	0.235	0.197	0.646	1.079	26.3	14.3
3.5	41510.00	0.245	0.202	0.595	1.042	26.3	14.3