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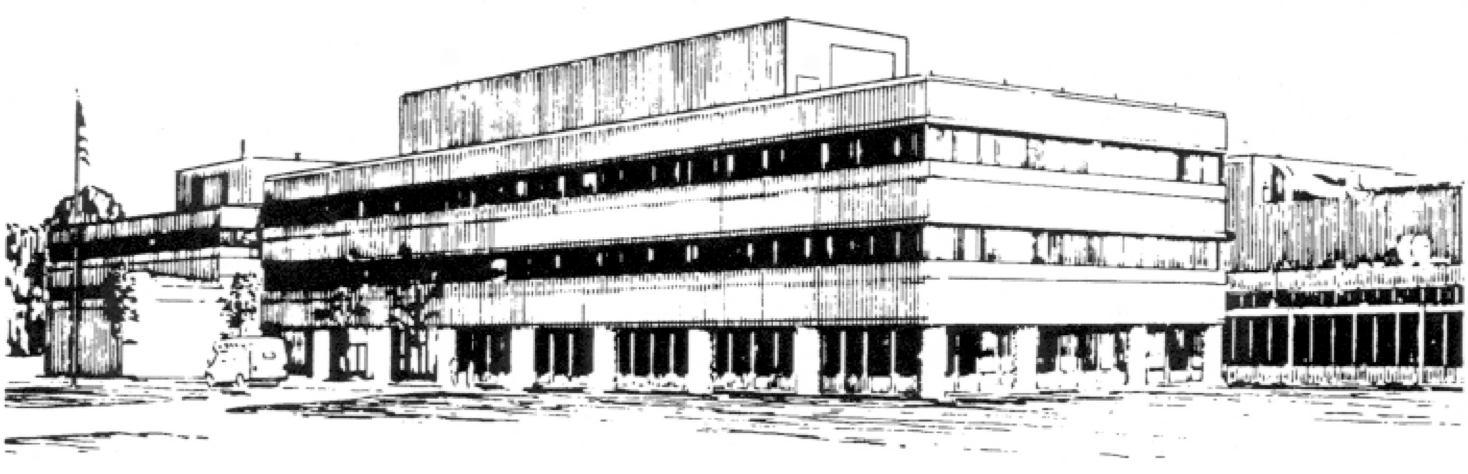

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Abstract-- **The low aspect ratio spherical torus (ST) configuration requires that the center stack design be optimized within a limited available space, using materials within their established allowables. This paper presents certer stack design methods developed by the National Spherical Torus Experiment (NSTX) Project Team during the initial design of NSTX, and more recently for studies of a possible next step ST (NSST) device.**

I. Introduction

Design point selection requires parametric study relying on simple analytic solutions to characterize performance in terms of plasma and engineering quantities, short of detailed analysis using, e.g. finite element methods. Many excellent papers have been written on this subject for conventional tokamaks [1] and also for STs [2,3]. This paper presents the method used by the NSTX team which includes some perhaps interesting new ideas being considered for NSST. The focus is on engineering issues related to pulsed copper/copper alloy magnets and, further, to the Toroidal Field (TF) and Ohmic Heating (OH) coils associated with the "center stack" of the ST device.

II. Design Issues

A. Requirements

Performance requirements for the TF system are the toroidal field B_t to be produced at radius R_0, and flat top duration. For the OH system the primary requirement is to produce a specified flux swing over the time of plasma current duration. Secondary requirements relate to the coil height, which determines the fraction of OH flux coupled to the plasma, and the stray field. Since the OH coil surrounds the inner legs of the TF coil in an ST, the OH coil also sets the TF height.

B. Engineering Constraints

While the complete design of the TF and OH coils and the integrated center stack requires detailed analysis of many aspects, the main design drivers are as follows.

- OH Coil
  - Conductor temperature rise and mechanical stress
- TF Coil Inner Legs
  - Conductor temperature rise and mechanical stress
  - Insulation shear stress
- Integrated Center Stack
  - Peak power, typically at start of flat top (SOFT)
  - Peak energy, typically at end of flat top (EOFT)
  - Overall height

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Methods for estimating these factors are presented herein (except for the TF insulation shear, which is highly dependant on the torque reaction scheme). However, it is emphasized that careful judgment is required in choosing allowables and margins. The challenge is to select, based on simple analysis, a design point which will withstand the scrutiny of detailed analysis with, in the end, satisfactory margins.

III. Methodology

Methods presented here are in use to study options for a next step ST. However, they are derived from earlier work on NSTX [4] and MAST [2] and can be applied more generally.

A. OH Coil

To rough-out the thermal and mechanical conditions, the following simplified OH waveform is assumed.

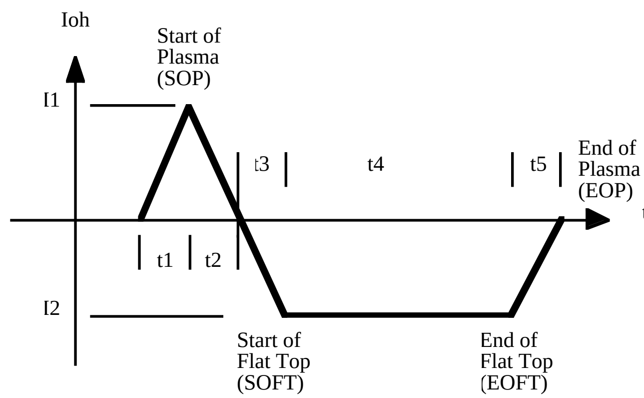

Fig 1. Simplified OH Current Waveform

OH conductor materials will be cooled, in the case the NSST, to liquid nitrogen (LN_2) temperature (80K) prior to the pulse and allowed to heat to 373K (100C) at the end of the pulse. Optimum performance is realized when materials are operated at their low temperature stress limit at SOP and their high temperature stress limit at EOFT, and at their thermal limit at EOP. Toward this end, for the OH waveform shown in Fig. 1, an asymmetry in the OH current waveform can be chosen to optimized performance. Assuming that the EM stress is due to Ioh only, then…

$$\frac{I_1}{I_2} = \sqrt{\frac{\sigma_{cold}}{\sigma_{hot}}} \equiv K_{asym} \tag{1}$$

A second benefit of asymmetric OH operation is reduced dissipation during the relatively long plasma flat top time. A third benefit is that the peak OH power which coincides with the peak TF power at SOFT is reduced, such that the total composite power peak imposed on the facility is reduced.

To maximize the flux swing available from the OH solenoid for NSST a novel approach has been identified which involves the use of a two part OH coil. Studies have shown that such a coil can increase the flux by 50% compared to a constant current density all-copper coil. The outer coil is wound with copper (Cu) conductor and is operated at a current density such that the material is at both thermal and mechanical limits. The minimum inner radius of the outer coil is determined by the allowable hoop stress. Then the inner coil is wound with a beryllium copper (BeCu) alloy material (C17510) and is operated at a current density such that the material is at either its thermal or mechanical allowable, which ever is limiting.

OH Thermal Calculations

The total I2T of the OH pulse is….

$$\sum I^2T = I_1^2\left(\frac{t_1}{3}+\frac{t_2}{3}\right)+I_2^2\left(\frac{t_3}{3}+t_4+\frac{t_5}{3}\right) \tag{2}$$

$$= I_1^2\left(\frac{t_1}{3}+\frac{t_2}{3}\right)+\frac{I_1^2}{K_{asym}^2}\left(\frac{t_3}{3}+t_4+\frac{t_5}{3}\right) \tag{3}$$

With equivalent square wave (ESW) current $I_{ESW} = I_1$….

$$T_{ESW} = \left(\frac{t_1}{3}+\frac{t_2}{3}\right)+\frac{\left(\frac{t_3}{3}+t_4+\frac{t_5}{3}\right)}{K_{asym}^2} \tag{4}$$

A 20% margin in temperature rise is allocated to nuclear heating and magnetoresistivity effects. For ordinary ohmic heating, curve fits are used to develop G ($=J^2T_{esw}$) functions for Cu and BeCu over the temperature range of interest.

$$G_{Cu}(T) = -6.45E16 + 1.02E15T - 2.61E12T^2 + 2.74E9T^3 \tag{5}$$

$$G_{BeCu}(T) = -1.54E16 + 1.93E14T - 3.02E10T^2 + 1.41E8T^3 \tag{6}$$

The current density J which is allowable given a temperature limit T_{allow} can be determined as follows…

$$J = \sqrt{\frac{G(T_{allow})-G(T_0)}{T_{ESW}}} \tag{7}$$

Given a packing fraction K_{pf} , then, the allowable current density has an average value of….

$$J_{avg} = JK_{pf} \tag{8}$$

OH Stress Calculations

The following formulae are used to estimate the conductor stress in the OH solenoid. Axial stress (relatively small) is ignored, and only the hoop stress is considered. For a two part OH solenoid, on the outer coil, the maximum hoop stress occurs at the inner bore of the coil [5] and can be estimated as follows.

$$\sigma = J*B\left\{\begin{array}{l}\dfrac{\left[(7+5\nu)R_o^4 - 8(2+\nu)R_oR_i^3 + 3(3+\nu)R_i^4\right]}{24(R_o - R_i)(R_o^2 - R_i^2)} \\ -\dfrac{(1+2\nu)R_oR_i}{3(R_o - R_i)} + \dfrac{(1+3\nu)R_i^2}{8(R_o - R_i)} \\ +\dfrac{R_o^2}{24}\left[\dfrac{(7+5\nu)R_o^2 - 8(2+\nu)R_oR_i + 3(3+\nu)R_i^2)}{(R_o - R_i)(R_o^2 - R_i^2)}\right]\end{array}\right\} \tag{9}$$

where:

R_o = outer radius of conductor pack
R_i = inner radius of conductor pack
ν = Poisson's Ratio

Here B is the field within the bore of the outer coil due to its own current….

$$B = \mu_0 J_{avg}(R_o - R_i) * ff \tag{10}$$

Where ff is the form factor which accounts for the finite length of the coil….

$$ff = \frac{\Delta Z}{\sqrt{\Delta Z^2 + \left[\frac{(R_o + R_i)}{2}\right]^2}} \tag{11}$$

and ΔZ is the height of the coil. The height of the OH coil needs to exceed that of the plasma by some amount to reduce leakage flux and minimize stray vertical field. Based on NSTX, a ratio between OH coil height and plasma height in the range 1.2 to 1.4 is typically assumed for NSST.

On the inner coil, the maximum hoop stress occurs at the inner bore of the coil, due to its own current plus the J x B force with the background field of the outer coil [5]….

$$\sigma = J*B\left\{\frac{(2+\nu)\left[2R_o^2 + R_oR_i + R_i^2 - \frac{(R_o + R_i)(1+2\nu)R_i}{2+\nu}\right]}{3(R_o + R_i)}\right\} \tag{12}$$

Here R_o and R_i are the outer and inner radii of the inner coil, J is the current density of the inner coil, and B is field due to the outer coil. Finally, the double swing flux produced by each part of the OH coil is equal to….

$$\Phi_{ds} = ff * \frac{\mu_0 \pi J_{avg}}{3}(R_o^3 - R_i^3)(1 + 1/K_{asym}) \tag{13}$$

OH Power and Energy Calculations

The peak power will occur just prior to Start of Flat Top (SOFT), at the end of the plasma current ramp up. To calculate the power, the coil inductance and resistance at SOFT needs to be calculated. Although this could be done on a one-turn basis, a particular number of turns is chosen to provide some idea of the power supply requirements. Assuming a current *I* per turn, the corresponding number of turns N for a particular field can be computed as follows.

$$N = \frac{B}{ff(\mu_0 I\ \Delta Z)} \tag{14}$$

On this basis the number of turns in the inner and outer coils can be calculated. Then the inductance of the OH coil, with a total of N_{oh} turns, is as follows…

$$L_{oh} = \frac{flux}{ampere - turns} = \frac{\Phi_{ds}}{(1+1/k_{asym})N_{oh} I} * N_{oh}{}^2 = \frac{\Phi_{ds} N_{oh}}{I(1+1/k_{asym})} \tag{15}$$

The G function can be used to estimate the temperature of the conductors at SOFT as follows.

$$G = G(T_o) + \Delta G \tag{16}$$

$$\Delta G = \int J^2(t) = \frac{I^2_{ESW}\ T_{ESW}}{CSA} \tag{17}$$

Curve fits are used to develop inverse G functions for Cu and BeCu as follows.

$$T_{Cu}(G) = 79.37 + 1.35E-15G + 6.29E-33G^2 + 1.38E-49G^3 \tag{18}$$

$$T_{BeCu}(G) = 80.55 + 5.63E-15G - 8.15E-33G^2 + 6.03E-49G^3 \tag{19}$$

With the temperatures known, the resistance of the inner and outer coils can be calculated using resistivity data as follows.

TABLE 1
RESISTIVITY CHARACTERISTICS

	Cu	BeCu
Resistivity ρ(μΩ-m) @ 293K	1.72	2.529
Temp coefficient α (deg^{-1}K)	0.0041	0.0025

The driving voltage at SOFT is…

$$V_{oh} = \frac{(I * R_{oh} + L_{oh} * I / t_3)}{K_{sym}} \tag{20}$$

The power is…

$$P_{soft} = V_{oh} * I \tag{21}$$

The peak energy requirement will occur at EOFT. Curve fits are used to develop the H functions (J/m^3) for Cu and BeCu. These functions relate the dissipated energy to the temperature rise, and are of the form…

$$H_{Cu}(T) = -1.54E8 + 1.41E6T + 5929.6T^2 - 5.29T^3 \tag{22}$$

$$H_{BeCu}(T) = -1.36E8 + 1.13eET + 7329.5T^2 - 7.54T^3 \tag{23}$$

The temperature of the coils is computed in the same manner as for SOFT. Then, the energy dissipation is…

$$\Delta H = H(T) - H(T_o) \tag{24}$$

$$W = \Delta H * CSA * L \tag{25}$$

Finally, total energy is the sum of dissipated and stored…

$$W_{eoft} = W_{diss} + 1/2 L_{oh}(I / K_{asym})^2 \tag{26}$$

B. TF Coil

The following simplified TF coil shape is assumed.

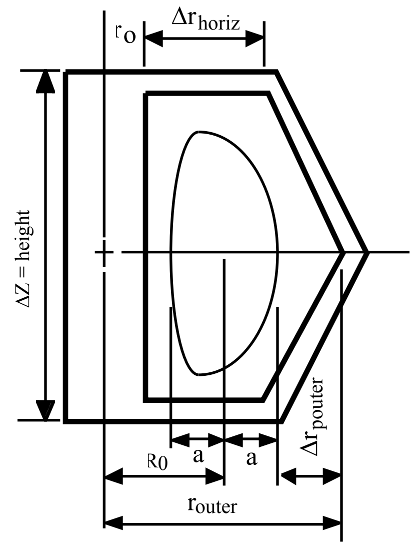

Fig. 2 Simplified TF Coil Representation

Based on NSTX , the ratio of TF coil height to plasma height TF in the range 1.6 to 1.8 is appropriate for NSST. The length of the horizontal limbs is assumed equal 2*a.

TF Thermal, Power, and Energy Calculations

Thermal performance of the coil is assessed by performing a simple simulation of the TF current waveform. The required current from N turns is…

$$NI = 2\pi \frac{R_o B}{\mu_0} \tag{27}$$

The inductance is obtained by integrating the flux enclosed as follows…

$$\Phi = \int_0^{router} \frac{\mu_0 I}{2\pi r} H(r) dr \tag{28}$$

where I is the current enclosed, which linearly increases from zero at r=0 to the full current I at the outer radius of the inner legs, and H(r) is the height of the bore of the coil, assumed equal to “height” out through the horizontal limbs, and then linearly decreasing to zero thereafter over the distance “Δr_{pouter}”. Then the inductance is…

$$L_{tf} = \frac{\Phi N^2}{I} \tag{29}$$

The total resistance of N series inner legs of the coil is…

$$R_{inner} = \rho \frac{LN}{A_{conductor}} \tag{30}$$

where L is assumed equal to "height" and ρ is the resistivity which varies with temperature and current, due to the magnetoresistivity effect. The fractional increase due to magnetorestivity can be described via a function F [6] where:

$$\mathrm{F} = 10^{(-2.662+0.3168X+0.6229X^2-0.1839*X^3+0.01827*X^4)} \tag{31}$$

$$X = \log_{10}\left[\frac{B}{(1+k(T-273))}\right] \tag{32}$$

B = average transverse field (B at r=70.7% of inner leg radius)
T = temperature of interest
k = temperature coefficient of resistance

Curve fits were used to develop a function for the specific heat of copper as follows.

$$Q_{Cu}(T) = -82.36 + 4.95T - 0.019T^2 + 2.5E-5T^3 \tag{33}$$

For small increments, temperature rise is approximated as…

$$\Delta T \approx \frac{I^2R}{Q(T)} \tag{34}$$

Outer leg resistance is assumed constant and equal to a fraction of the inner leg resistance at maximum temperature.

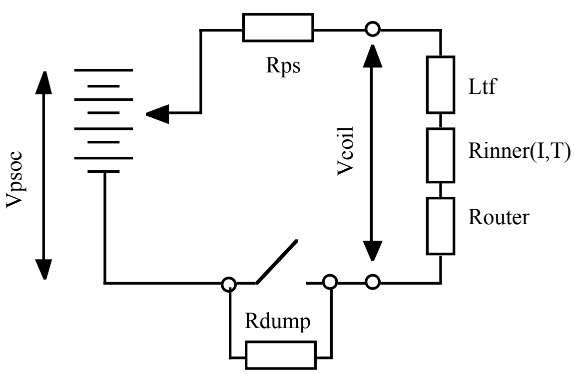

Fig. 3. TF Equivalent Circuit

The simulation circuit is shown in figure 3. A dump resistor, normally bypassed, can be introduced if the power supply trips at full current, thereby reducing the L/R time constant and the additional dissipation which must be anticipated. Circuit response is simulated using Euler integration…

$$\Delta I = \frac{\left[V_{psoc} - I\left(R_{ps} + R_{inner} + R_{outer}\right)\right]\Delta t}{L} \tag{35}$$

with the inner leg temperature and resistance updated each time step. Flat top must end when the prospective temperature rise due to an L/R decay of the current would bring the final temperature to the limit. This is estimated by taking the total stored energy, apportioning it between the inner and outer legs and dump resistor in proportion to their resistances, and dividing by the heat capacity…

$$\Delta T_{LR} = \frac{\left[1/2LI^2\right]\frac{R_{inner}}{\left(R_{inner}+R_{outer}+R_{dump}\right)}}{Q} \tag{36}$$

TF Stress Calculations

To assess the inner leg stresses, the outer leg contribution to the vertical force needs to be included. An optimum outer leg is moment-free and imposes minimal vertical load on the inner legs by using a "bow" shaped constant tension form. Variations described herein further develop earlier bow coil concepts [7] so as to achieve practical dimensions.

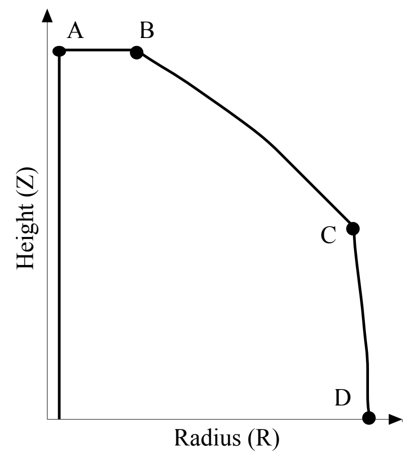

Fig. 4 Path of Current Center of TF Outer Leg

In figure 4, "A" is located at the radius of the effective current center of the inner leg. The segment between "A" and "B" is the radial flag. The segment between "B" and "C" is a constant tension section of the outer leg. At "C" a force can be applied by a structural ring to alter the shape of the outer leg. The segment between "C" and "D" is another constant tension section. "D" corresponds to the outer leg current center intersection with the midplane.

The total integrated vertical force on the outer leg in one half plane is independent of the path taken from points A to D.

$$F_v = \int_{r1}^{r2} I_r(r)B_\varphi(r)dr = \frac{1}{2}\frac{\mu_0 I^2}{2\pi}\ln\left(\frac{R_2}{R_1}\right) = \frac{IB_0R_0}{2}\ln\left(\frac{R_2}{R_1}\right) \tag{37}$$

where:

$I_r(r)$ = radial component of TF current at radius r
$B_\varphi(r)$ = toroidal field at radius r, avg. across conductor
B_0 = toroidal field at plasma major radius R_0
R_2 = radius to current center in outer leg (point A)
R_1 = radius to current center in inner leg (point D)

It is noted that, in the above derivation:

$$B_\varphi(r) = \frac{1}{2}\left[\frac{\mu_0 I}{2\pi r}\right] \tag{38}$$

due to the fact that B varies from maximum at the inside of the outer leg to zero on the outside, so the current interacts, on average, with 1/2 of the value of B on the inside. For the inner leg, with circular cross section extending to the outer radius r_o:

$$F = \int_{r=0}^{r=ro} I(r)B(r)dr = \frac{\pi\mu_0 J^2 r_o^4}{8} = \frac{\mu_0 I^2}{8\pi} \tag{39}$$

An equivalent representation consists of a filament proceeding from an effective current center at R_1 and then to r_o which produces the same total integrated force:

$$F = \int_{r=R1}^{r=ro} I(r)B(r)dr = \frac{\mu_0 I^2}{2\pi}\ln\left(\frac{r_o}{R_1}\right) \tag{40}$$

Equating the above two results produces the following for R_1:

$$R_1 = \frac{r_o}{\varepsilon^{1/4}} = 0.78 r_o \tag{41}$$

For the outer leg the current center coincides with the simple geometric center of the conductor.

The relative fractions of F_v which are applied at points A and D can be controlled by tailoring the shape of the outer leg. The constant tension *T* shape is obtained by joining together constant tension arc segments such that:

$$\rho = \frac{dS}{d\theta} = \frac{T}{P} \tag{42}$$

where:

ρ = radius of curvature	θ = arc angle
S = arc length	P = force per unit length

If *f* is the fraction of the total vertical force allowed to appear on the inner leg then the constant tension curve can be generated by numerical integration of:

$$\frac{\Delta S}{\Delta\theta} = (1-f)*r*\ln\left(\frac{R2}{R1}\right) \tag{43}$$

The limit on vertical force which can be applied to the inner leg depends on the other components of stress arising from EM and thermal effects. The flow of TF current causes an inward "pinching" force on the column, as well as torsion arising from the JxB force with the poloidal fields. The pinching causes compression which is maximum at the center, whereas the torsion causes shear which is maximum at the outer edge of the inner leg. It is assumed that the former is the limiting factor, so the shear stress neglected in this analysis. With constant current density the inward radial force within the inner leg conductor varies linearly with radius since:

$$B = \frac{\mu_0 I}{2\pi r} = \frac{\mu_0 J r}{2} \therefore JxB = \frac{\mu_0 J^2 r}{2} \tag{44}$$

This situation is similar to that of a rotating cylindrical shaft where the centrifugal force is proportional to radius. Approximate formulae [8] for the principal stresses are:

$$\sigma_{rr} = \left(-\frac{B_{\max}{}^2}{2\mu_0}\right)\left(\frac{3-2\nu}{2(1-\nu)}\right)\left(1-\left(\frac{r}{a}\right)^2\right) \tag{45}$$

$$\sigma_{\varphi\varphi} = \left(-\frac{B_{\max}{}^2}{2\mu_0}\right)\left(\frac{3-2\nu}{2(1-\nu)} - \frac{1+2\nu}{2(1-\nu)}\left(\frac{r}{a}\right)^2\right) \tag{46}$$

$$\sigma_{zz} = \left(-\frac{B_{\max}{}^2}{2\mu_0}\right)\left(\frac{\nu}{1-\nu}\right)\left(1-2\left(\frac{r}{a}\right)^2\right) \tag{47}$$

where:

r = radius within conductor	a = outer radius of conductor
ν = Poission's ratio	B_{max} = B at r=a, $B_{ma} = \mu_0 I/2\pi a$

The combined (Von Mises) stress can be calculated as….

$$\sigma_{VonMises} = \sqrt{\frac{(\sigma_{rr}-\sigma_{\varphi\varphi})^2 + (\sigma_{\varphi\varphi}-\sigma'_{zz})^2 + (\sigma'_{zz}-\sigma_{rr})^2}{2}} \tag{48}$$

where…

$$\sigma_{zz}' = \left(-\frac{B_{\max}{}^2}{2\mu_0}\right)\left(\frac{\nu}{1-\nu}\right)\left(1-2\left(\frac{r}{a}\right)^2\right) + \Delta \tag{49}$$

…and Δ is the stress due to the vertical force EM force F_v as well as pre-compression and/or thermally induced stresses along the z axis. Allowing for a pre-compression force F_0, along with an additional force F_s due to thermal expansion, where $F_s = k\Delta L$, k being the spring constant of the structure:

$$\Delta = \frac{f*F_v - (F_0 + k\Delta L)}{A_{net}} \tag{50}$$

The design must consider the expected temperatures at start of pulse (SOP), start and end of flat top (SOFT, EOFT), and end of pulse (EOP), combining the EM forces only for the SOFT and EOFT states. The parameters to be adjusted include:

- Fraction *f* of vertical force allowed on inner leg
- Values of pre-compression F_0 and spring constant *k*
- Location (r,z) and force at "C", location (r) of "B"

The optimum pre-compression force results in a balance between the fraction of allowable stress at SOFT and EOP.

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