# Digital Coil Protection (DCP) for NSTX Center Stack Upgrade

C Neumeyer, R Woolley

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# Outline

- Background
- Description of existing protection systems
- General requirements related to DCP
- Design considerations for DCP
- Implementation plan
- Summary

# Background (1)

- Coil protection objectives

  1. Prevent thermal overload of coils

  2. Prevent mechanical/structural overload

     - Coils
     - Structures carrying loads generated by coils

*Other coil-related protection (e.g. ground fault protection) is necessary but existing systems are adequate for upgrade and are not considered in scope of DCP*

# Background (2)

1. Prevent thermal overload of coils

- Avoid current pulses with $\int i^2(t)dt$ exceeding coil capacity
  - Coils ~ adiabatic during pulses where duration << cooling time
  - Temperature rise $\Delta T \propto \int i^2(t)dt$
  - Max temperature depends on initial temp and temperature rise

$$T_{\max} = T_0 + \Delta T$$

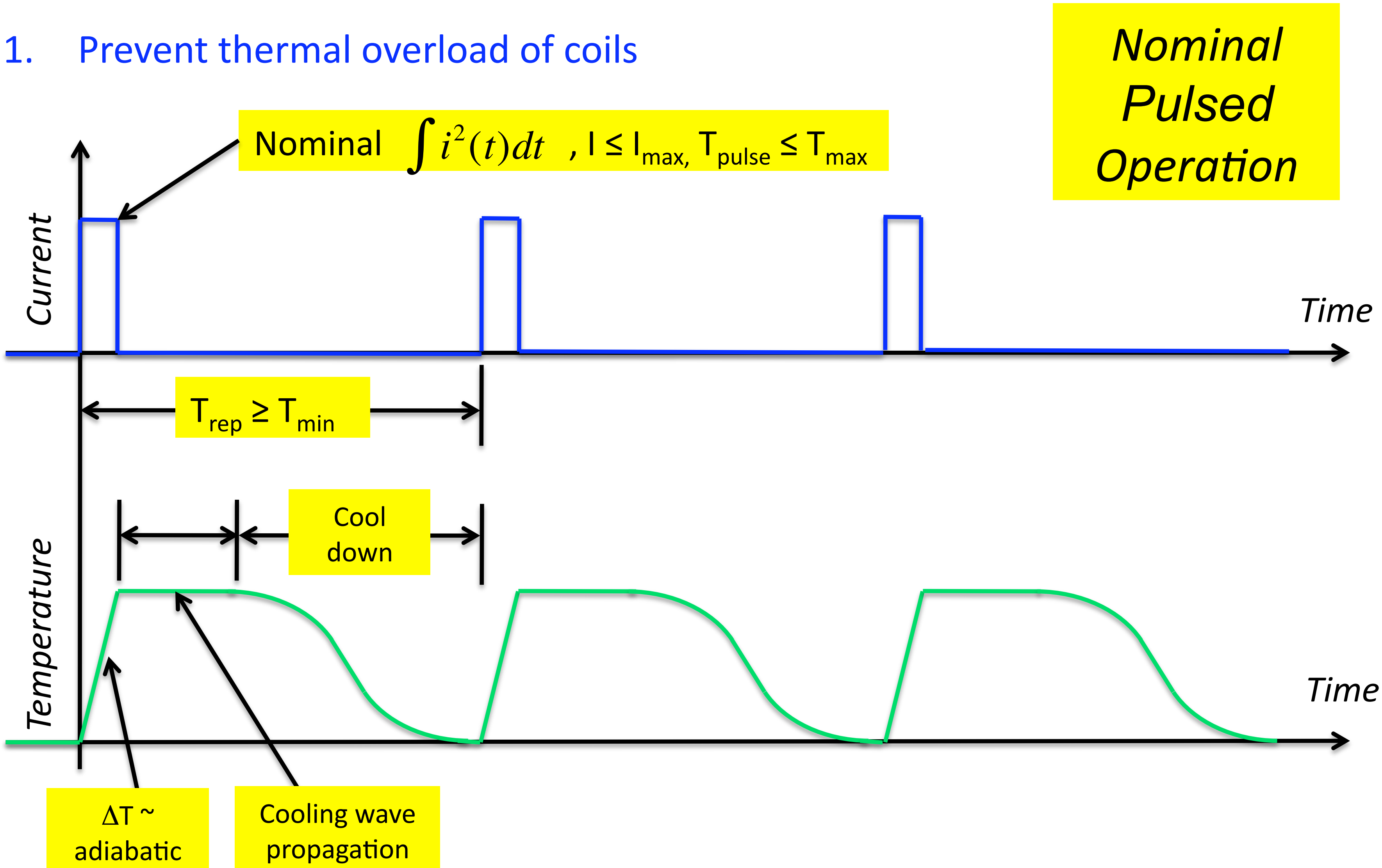
- Avoid root mean square (rms) current exceeding coil capacity
  - Coils cool down between pulses
  - Cooling time ranges from 10's to 100's of seconds
  - RMS current depends on $\int i^2(t)dt$ and repetition period $T_{rep}$

$$I_{rms} = \sqrt{\frac{\int i^2(t)dt}{T_{rep}}}$$

  - For a given $\int i^2(t)dt$ a minimum repetition period is required

# Background (3)

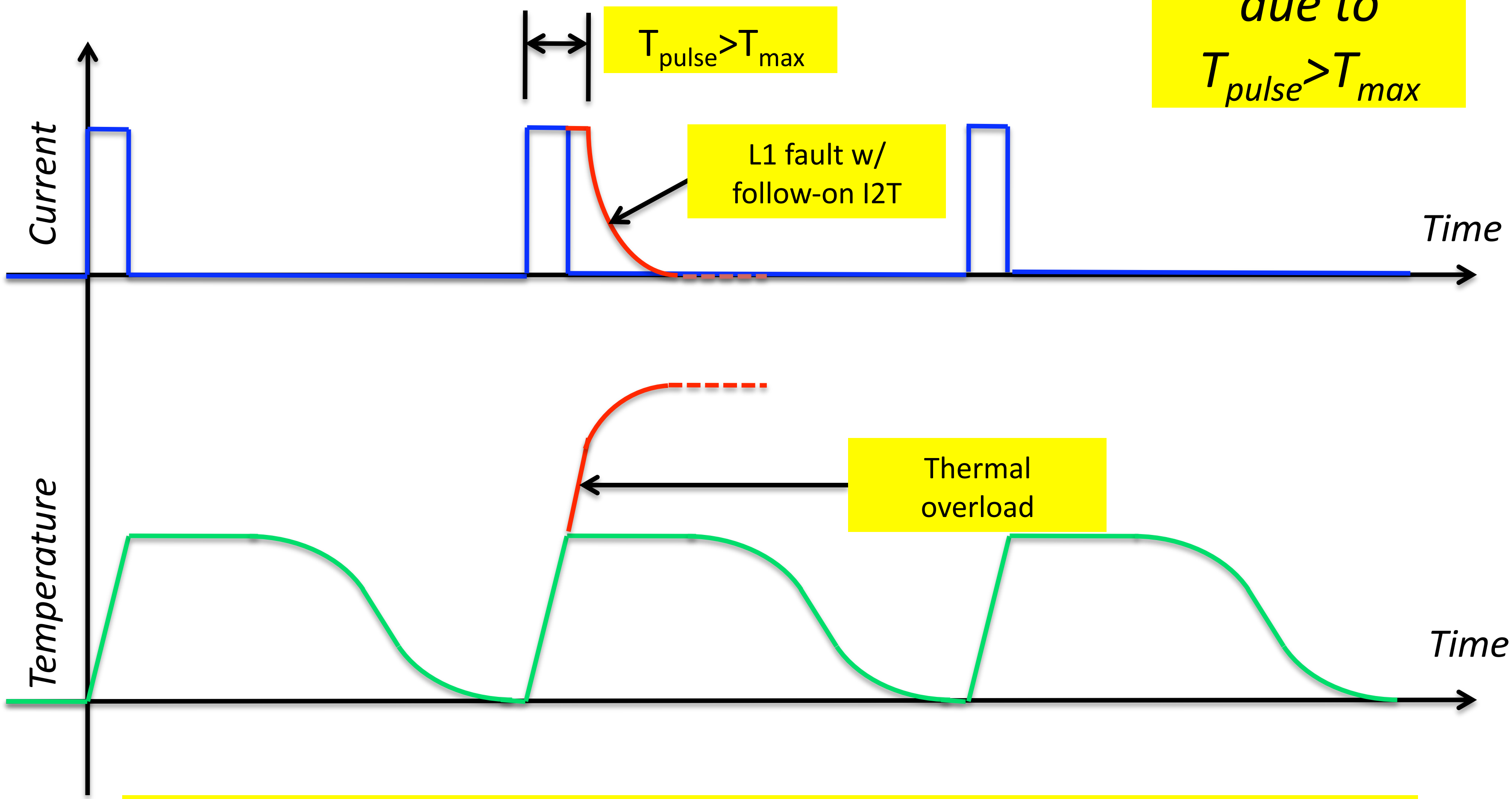
1. Prevent thermal overload of coils



# Background (4)

1. Prevent thermal overload of coils

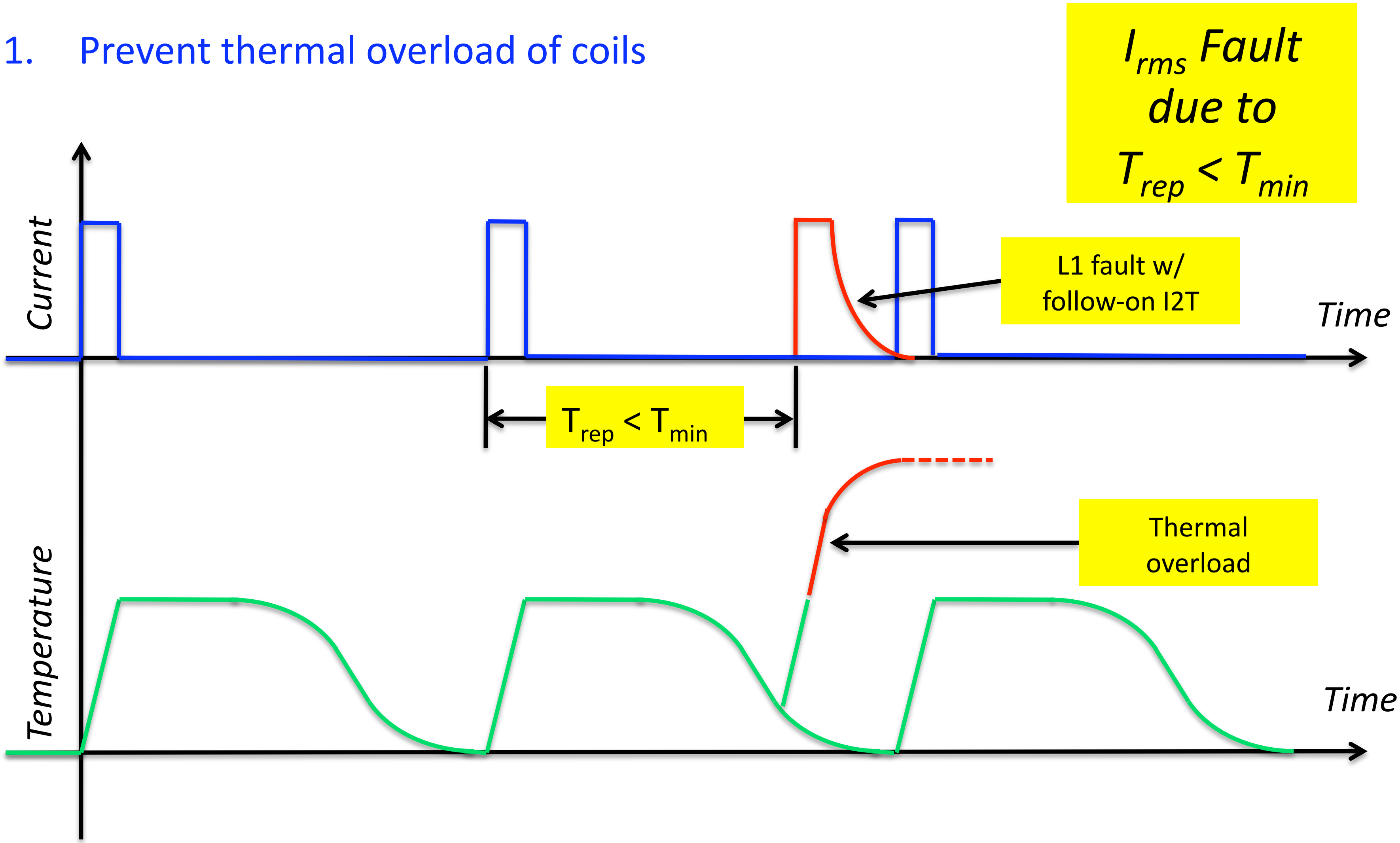
*$I^2T$ Fault due to $T_{pulse} > T_{max}$*




Similar fault if i(t) results in excess $I^2T$ while $|I|$ and $T_{pulse}$ within protection limits

# Background (5)

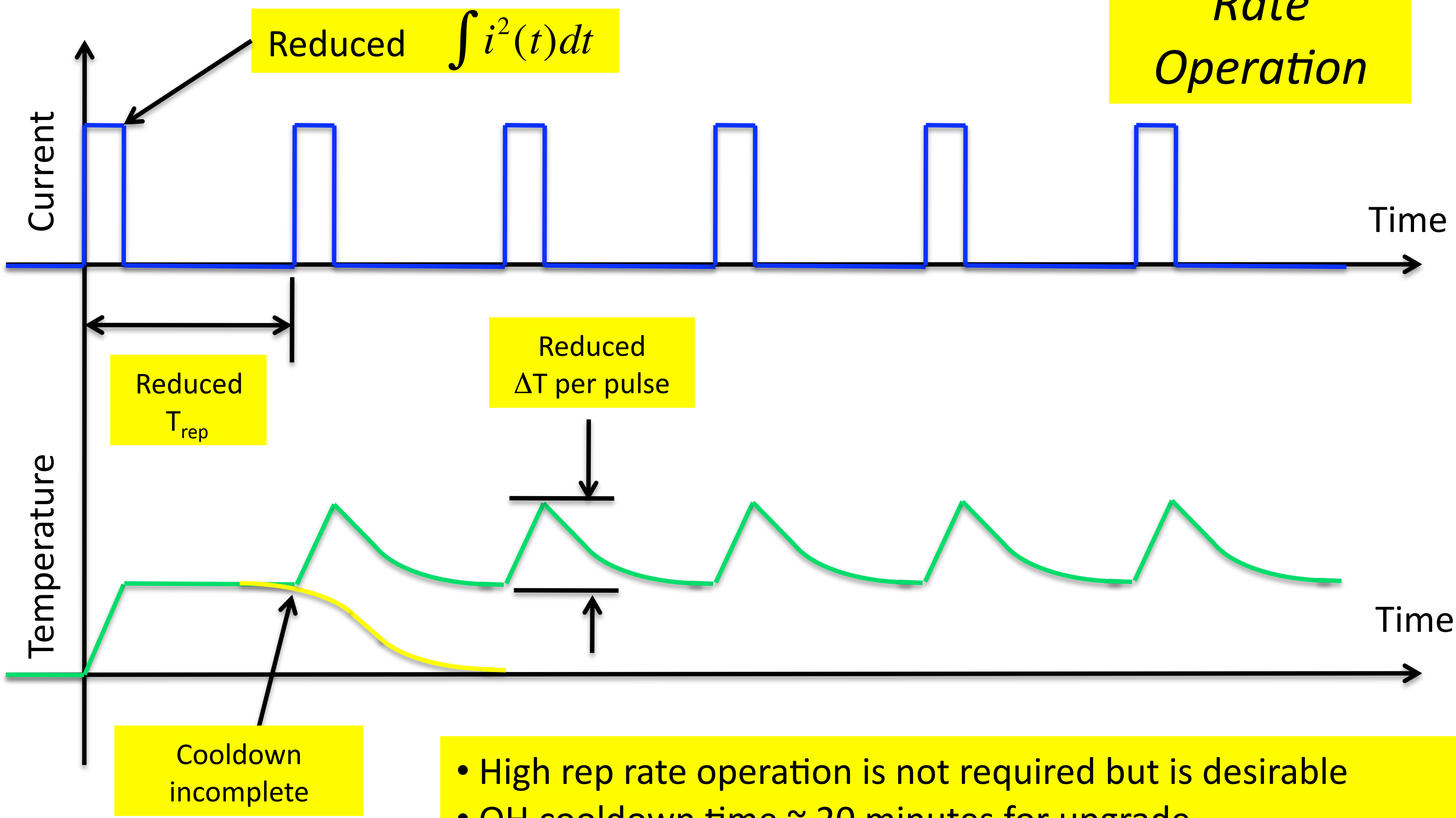
1. Prevent thermal overload of coils



# Background (6)

1. Prevent thermal overload of coils

*High Rep Rate Operation*




- High rep rate operation is not required but is desirable
- OH cooldown time ~ 20 minutes for upgrade

# Background (7)

2. Prevent mechanical/structural overload

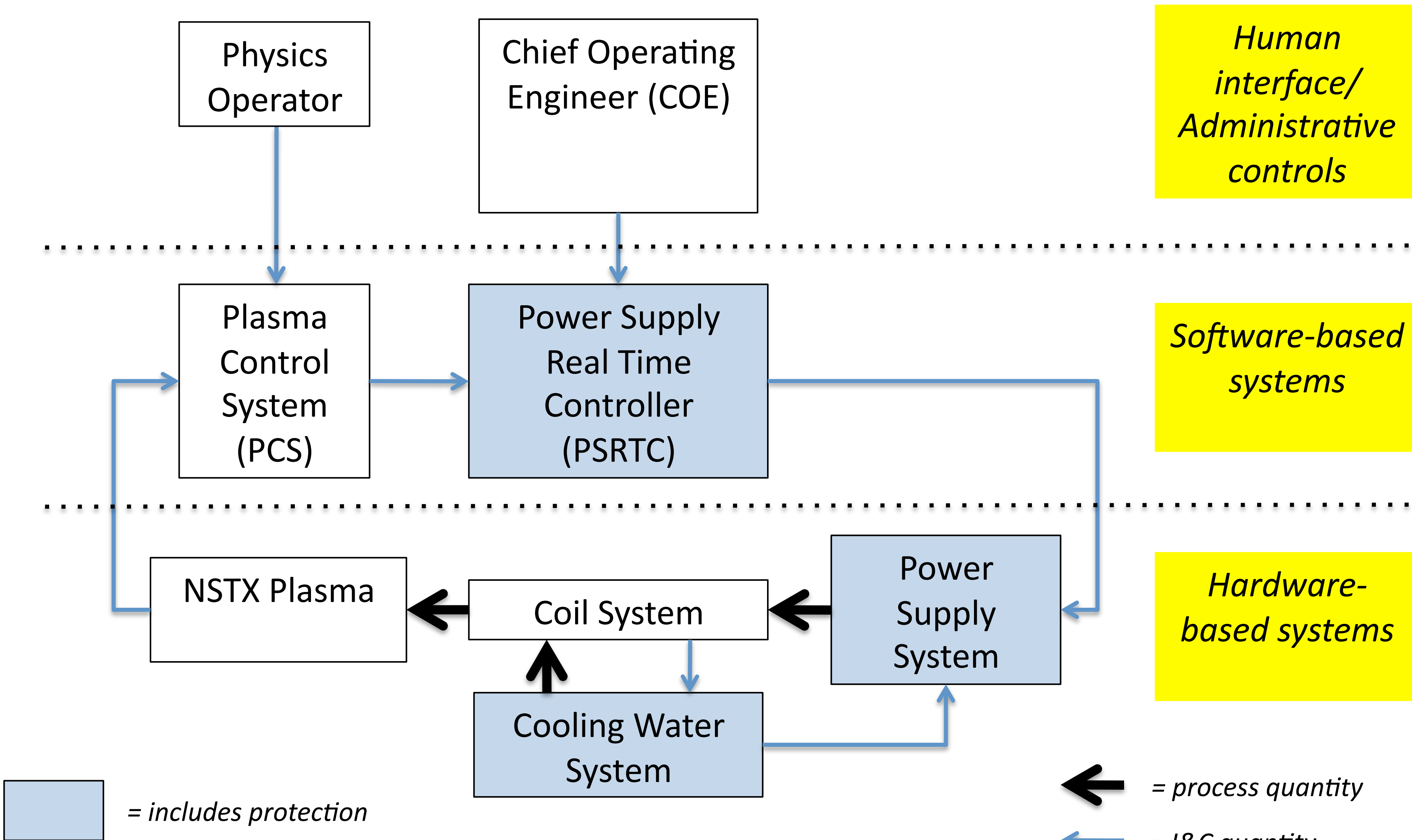
- Coils
  - Stresses in conductor and insulation
    - » Stress due to J x B Lorentz forces
      - Force in coil due to J in coil
      - B due to net effect of all coils and plasma
    - » Stress due to thermal effects (expansion and gradient)
    - » Allowables a function of temperature
- Structures carrying loads generated by coils
  - Stresses in structures
    - » Stress due to J x B Lorentz coil force combinations
      - Force carried by structure depends on structural design
      - Load sharing depends on elasticity of multiple load paths
    - » Stress due to thermal effects (expansion and gradient)

# Background (8)

2. Prevent mechanical/structural overload

- Load paths requiring DCP
  - PF coil supports
  - OH and PF conductors
  - OH launch load on compression washers
  - TF flex connector
  - TF inner leg torsion
  - TF outer leg support system

# Existing Protection Systems (1)



# Existing Protection Features (2)

- PSRTC*
  - Instantaneous current |I| limits
  - $I^2T$ limits per pulse
  - Thermal simulations and temperature limits
    - Single time constant models
      - Coils
      - Cables
  - Force limits
    - Fr and Fz limits
  - Other limits
    - Several force combinations related to TF joint

**somewhat prototypical of Digital Coil Protection system*

# Existing Protection Features (3)

- Power Supply System
  - Analog Coil Protection (ACP)
    - Instantaneous overcurrent limits based on |I|
    - Overtime limits based on pulse duration
    - Rep rate limits based on repetition period
    - Thermal simulations based on $I^2T$
      - Single time constant model
      - Now RWM only, but coverage for all coils included as part of CS upgrade package
  - Rochester Instrument Sys (RIS) (TF,OH,PF2,PF3)
    - Instantaneous overcurrent limits based on |I|
    - Thermal simulation based on $I^2T$
      - Single time constant model
      - Anticipatory "1/2 $LI^2$" module from TFTR era is no longer in use

# Existing Protection Features (4)

- Power Supply System (con't)
  - Transrex AC/DC converters
    - Overcurrent limits based on |I|
    - Overtime limits based on pulse duration
  - AC feeder breakers
    - Overcurrent limits based on |I|
    - Overtime limit based on pulse duration
  - Pulse Duration and Period (PDP) timer
    - Overtime limit based on pulse duration
    - Rep rate limit based on repetition period
  - PF4/5 Interlock* (new)
    - Limits forces/stresses in PF4/5 support structures based on algorithms
    - Implemented in Digital Signal Processor (DSP)
- Cooling Water System
  - Water Systems PLC interlock with power supply permissive
    - Water flow (all paths) must be > setpoint
    - Water inlet temperature must be < setpoint
    - OH water outlet temperature must be < setpoint

**somewhat prototypical of Digital Coil Protection system*

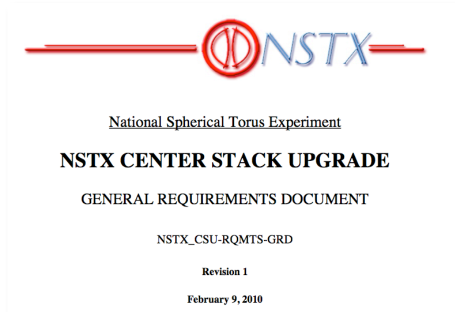
# Existing Protection Features (5)

- Coordination
  - Spreadsheet used to set operating envelope per admin procedure ISTP-001
    - Settings of various limits are coordinated with increasing levels of “headroom” such that trips should occur sequentially
    - Typ. PSRTC (1%), ACP (2%), RIS (5%), Transrex (5%), AC Feeder (15%)
  - OH duty cycle control per admin procedure
    - Rep period is selectable (300, 450, or 600 sec)
    - Facility clock setup per rep period selection
    - All $I^2T$ limits set based on rep period
    - Water System PLC OH outlet temperature interlock with power supply permissive is set based on selected rep period
  - PF4/5 overcurrent limits set via admin procedure whenever PF4 is energized (PF4 normally not used)
    - Recently (this run period) superseded by PF4/5 interlock

# Existing Protection Features (6)

- Features of existing system requiring improvement for upgrade
  - Reliance on various timers and OH coil outlet water temperature interlock to control duty cycle is simple and reliable but….
    - Lacks flexibility for high rep rate operation
    - Limits utilization of coil capacities
  - Mechanical/structural protection needs to be expanded
    - More force combinations need to be computed and limited in PSRTC
    - Protection based on force needs to be implemented in dedicated device
      - Independent from control computer
      - Not susceptible to operator error
  - RIS is obsolete, imprecise, difficult to adjust and calibrate

# General Requirements Related to DCP (1)


NSTX

National Spherical Torus Experiment

**NSTX CENTER STACK UPGRADE**

GENERAL REQUIREMENTS DOCUMENT

NSTX_CSU-RQMTS-GRD

**Revision 1**

**February 9, 2010**

2.2.4.d

“For engineering purposes, the nominal design requirement for all components and systems shall be based on the assumption that any combination of PF coil currents up to 100% of their ampere-turns, with either polarity of OH current at 100% of its ampere-turns and with Ip=0 or $\neq$ 0, shall be allowable……. In the event that this design requirement cannot be satisfied without significant cost impact and/or technical risk, exception may be taken. In this case:

•the design requirement may be reduced from the assumption of maximum possible currents to the PF/OH current distributions derived from the range of plasma equilibria specified by the physics requirements……

•the relationship between the design-driving quantity and the PF/OH currents and the plasma current shall be determined and described by an algorithm to be used in the control software and in real-time coil protection systems including the existing Analog Coil Protection (ACP...) and a new Digital Coil Protection (DCP, including capability of programmable algorithms) ”

# General Requirements Related to DCP (2)

3.5.5

The existing Rochester Instruments System (RIS) protection system shall be replaced by a new Digital Coil Protection (DCP) system. The DCP shall include the following features:

•Protection against ….over-current and $\int i^2(t)dt$ limits …..(same functionality as existing RIS)

•Simulation of heating and cooling …..using the coil currents as input, and protection against over-temperature

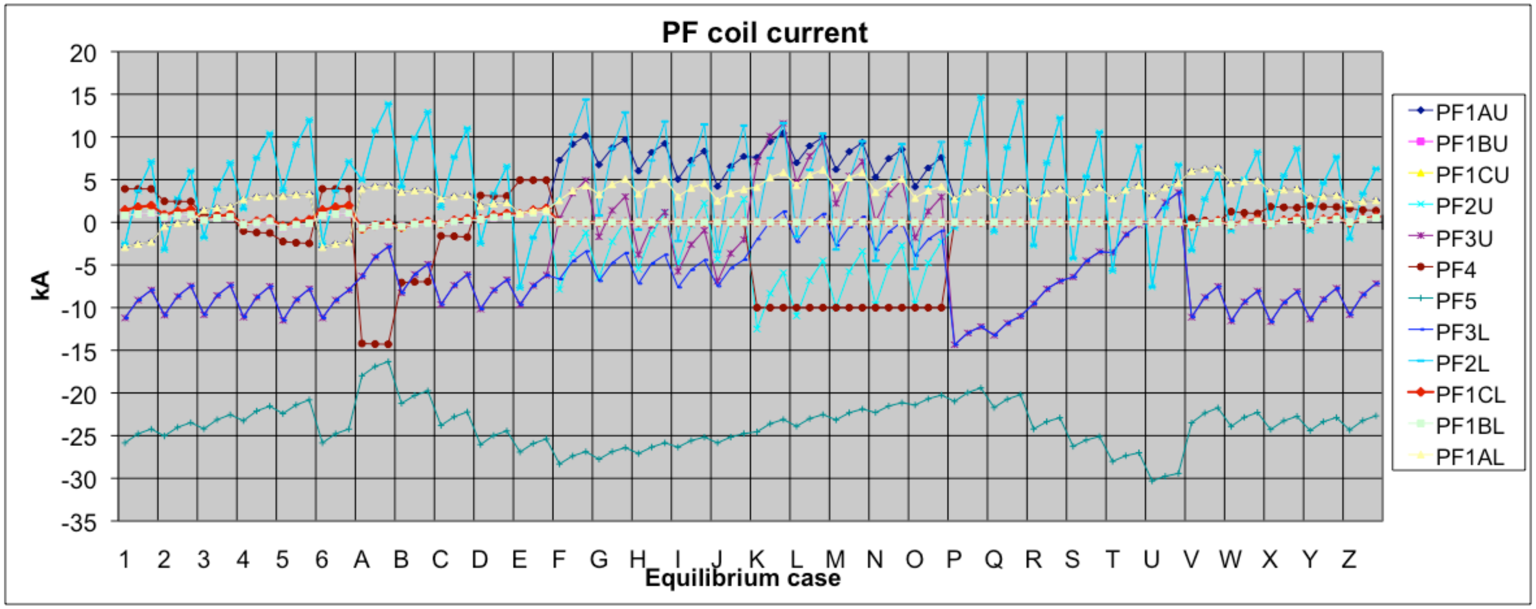
•Simulation of various design-limiting quantities based on algorithms using the coil currents as input, and protection against design limits (see section 2.2.4 d)

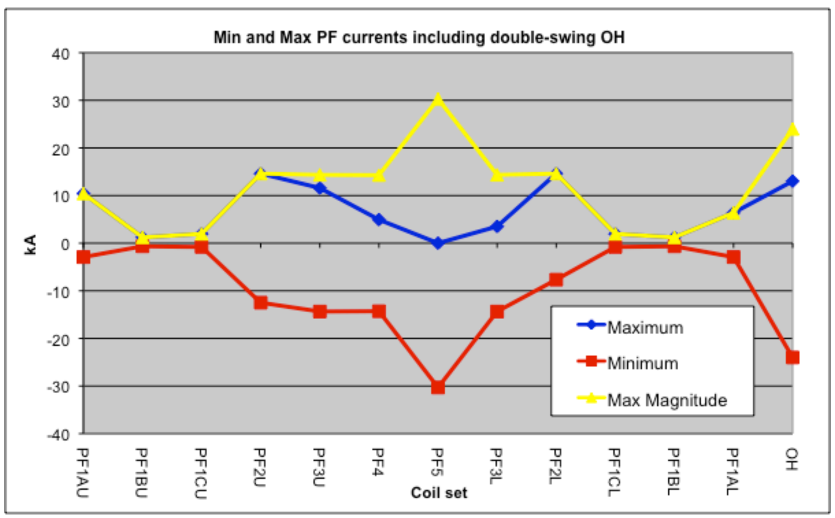
The DCP shall be designed and implemented such that its probability of failure is "Extremely Unlikely (per Table 2.5)"

| | | | |
|---|---|---|---|
| Extremely Unlikely Events | Events which are limiting faults and are not expected to occur during the lifetime of a facility but are postulated because of their safety consequences | 10-4>P≥10-6 | Facility damage may preclude returning to operation |

*Table 2-5 is coordinated with NSTX Structural Design Criteria and FMEA*

# General Requirements Related to DCP (3)




- PF currents have been specified by Physics for 32 plasma equilibria cases with $I_{oh}$ = -24/0/+24kA, total 96

- Power supply current +/- limits have been established with 10% headroom allowance and rounding to nearest kA

# General Requirements Related to DCP (4)

- Fr and Fz have been calculated for each coil for including:

  - Min/max from 96 equilibria
  - Min/max from worst case power supply limits

| Fr(tonne) | PF1aU | PF1bU | PF1cU | PF2U | PF3U | PF4U | PF5U | PF5L | PF4L | PF3L | PF2L | PF1cL | PF1bL | PF1aL | OH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min | -5 | -1 | -28 | -40 | -40 | -49 | 43 | 43 | -49 | -21 | -40 | -28 | -1 | -5 | 0 |
| Worst Case Min | -151 | -97 | -147 | -129 | -94 | -67 | 0 | 0 | -67 | -94 | -129 | -147 | -97 | -151 | -584 |
| Max | 144 | 32 | 10 | 52 | 115 | 122 | 240 | 240 | 122 | 115 | 52 | 10 | 32 | 57 | 17289 |
| Worst Case Max | 658 | 121 | 162 | 182 | 220 | 214 | 309 | 309 | 214 | 220 | 182 | 162 | 121 | 658 | 21211 |

| Fz(tonne) | PF1aU | PF1bU | PF1cU | PF2U | PF3U | PF4U | PF5U | PF5L | PF4L | PF3L | PF2L | PF1cL | PF1bL | PF1aL | OH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min | -26 | -14 | -14 | -31 | -68 | -93 | -110 | -23 | -39 | -14 | -20 | -31 | -22 | -22 | -7 |
| Worst Case Min | -97 | -66 | -76 | -88 | -138 | -192 | -238 | -87 | -69 | -112 | -87 | -65 | -41 | -143 | -247 |
| Max | 31 | 22 | 31 | 20 | 46 | 39 | 23 | 110 | 85 | 68 | 25 | 14 | 14 | 26 | 6 |
| Worst Case Max | 143 | 41 | 65 | 87 | 112 | 69 | 87 | 238 | 192 | 138 | 88 | 76 | 66 | 97 | 247 |

- 28 additional criteria (force combinations and moments) have also been generated

- Total 15 * 2 + 28 = 58 load criteria have been generated

- Posted and maintained up-to-date at:

  http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

# DCP Design Considerations (1)

- DCP system design is underway, and various issues are being evaluated. Present assumptions are **highlighted** in the following

- Design considerations fall into two categories
  - Hardware/software implementation
  - Algorithms
    - Thermal simulation
    - Electrical/electromagnetic modeling issues
    - Format for mechanical/structural algorithms
    - PSRTC version of algorithms

# DCP Design Considerations (2)

- Hardware/software implementation
  - DCP redundancy: **Dual redundant DCPs**
  - Computational requirements
    - Number of algorithms of each type: **~ 100 force-based, 14 thermal (one per coil)**
    - Update rate for each type: **1mS force-based, 10mS thermal**
  - Inputs/Outputs
    - **Redundant current measurements for each coil plus plasma current**
    - **Separate outputs to TF and PF/OH L1 fault line**
  - User interface requirements
    - **Local secure user interface for set-up**
    - **Interface with NSTX control system (EPICS) inc'l pre/post event signal digitization and display**
  - Processor, operating system and programming langauge
    - **X86 architecture, multiple processors as required**
    - **LINUX OS**
    - **programmed in C and/or FORTRAN**
  - Programming approach
    - **Modular code amenable to validation and verification**
    - **Finite State Machine approach to ensure deterministic behavior**
      - **Avoid conditional loops in real time code**

# DCP Design Considerations (3)

- Algorithms
  - Thermal simulation
    - **Wendroff finite-difference method including "cooling wave" effect**
      - » **Computationally efficient, suitable for real-time implementation**
      - » **Already developed and tested**
      - » **Will be conservative since inlet water temperature and flow rates will be based on trip settings in Water Systems PLC**
    - **Existing system of duty cycle timers and outlet water interlock**
      - **Will be retained**
        - » **Selector switch for multiple high duty factor repetition periods will be provided as per present practice**
        - » **After benchmarking and gaining experience with DCP, setpoints will be adjusted such that system provides back-up to DCP**

# DCP Design Considerations (4)

- Algorithms
  - Electrical/electromagnetic modeling issues
    - Plasma modeling
      - **Plasma current included in field/force calculation**
      - **PF/OH current shifts due to disruption pre-calculated and factored into algorithms**
    - Post-detection transient current overshoot
      - **Overshoot during time between fault detection and power supply bypass (voltage zero) pre-calculated and factored into algorithms**
    - Level 1 fault decay transient
      - **Possible transient increase in PF/OH currents during decay of mutually coupled circuits pre-calculated and factored into algorithms**
    - Follow-on $I^2T$ during Level 1 decay transient
      - **Fixed value of follow-on $I^2T$, based on rated current, factored into algorithms**

# DCP Design Considerations (5)

- Algorithms
  - Format for mechanical/structural algorithms
    - EM forces ($F_r$, $F_z$, $F_\theta$) on current carrying elements are related to currents by influence matricies

$$F_i = I_i \sum_j C^F_{i,j} I_j$$

    - Stresses ($\sigma_r$, $\sigma_z$, $\sigma_\theta$) on load paths arise from the sum of contributions from all forces

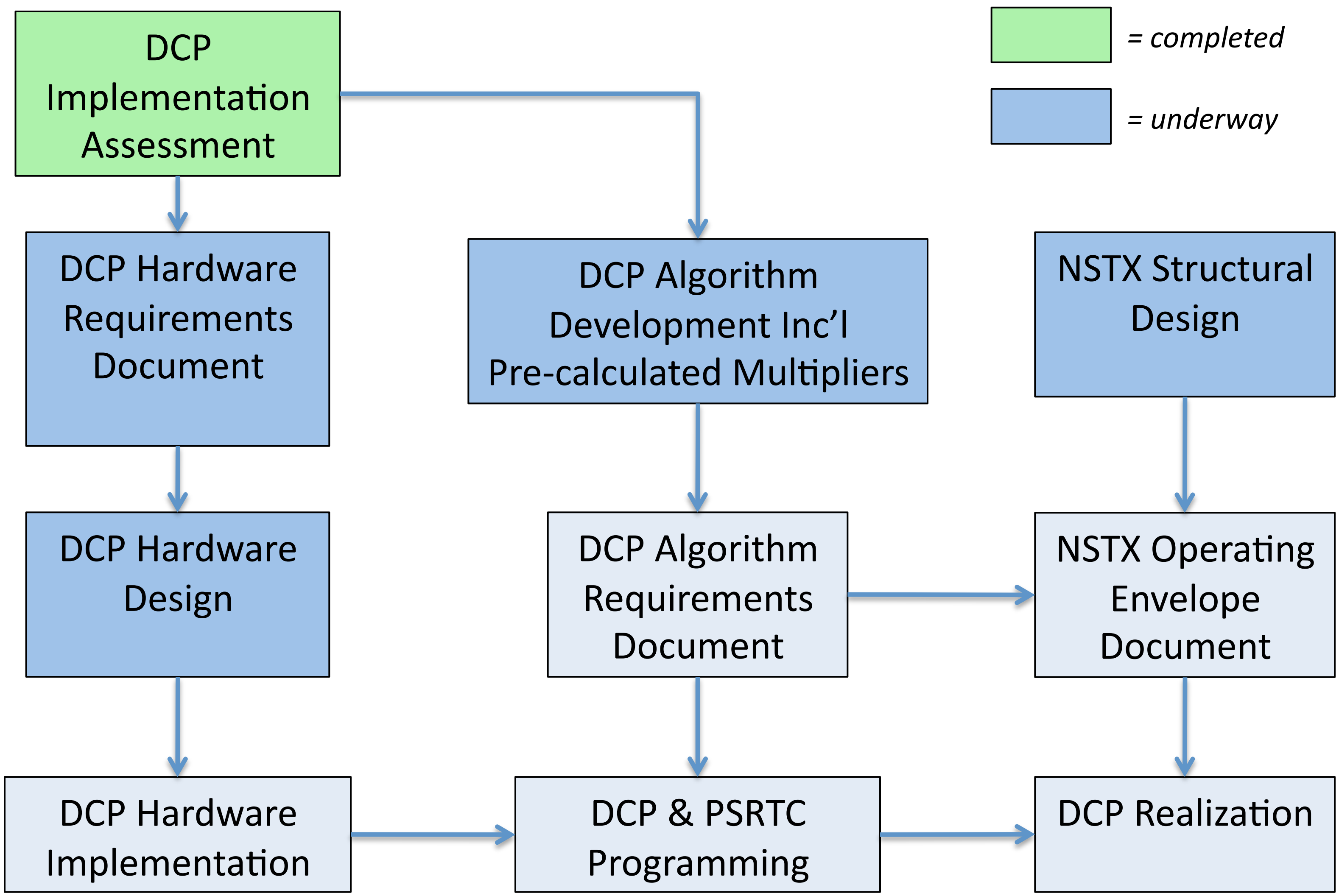
$$\sigma_i = \sum_j C^\sigma_{i,j} F_j$$

    - Stress allowables are typically expressed in terms of combined (Tresca or Von Mises) stress
    - **Multiple algorithmic formats will implemented for specification of limits as required**
      - **Forces on individual coils**
      - **Weighted sums of forces**
      - **Combined stresses**
    - **Limits will be reduced to basic weighted sums for computational efficiency**
    - **Effect of thermal stresses will be predetermined and factored into allowables**

# DCP Design Considerations (6)

- Algorithms
  - PSRTC version of DCP algorithms
    - PSRTC is presently used to guide machine operations
      - Hardware-based protection limits are coordinated with, and duplicated in PSRTC software
      - Waveforms of limiting quantities can be observed using PSRTC operator interface
        - » Simulation mode
        - » Actual shots
    - **DCP algorithms will be duplicated in PSRTC**
      - **Above advantages will be continued**
      - **PSRTC provides redundancy to DCP**
        - » **Reliability is diminished by linkage with NSTX computer network and COE but failure rate is still very low**

# Implementation Plan



# Summary

- NSTX Center Stack Upgrade requires a new coil protection system
  1. Improved mechanical/structural protection
  2. Improved thermal protection
- Digital Coil Protection (DCP) system will satisfy this requirement
- DCP development is underway
  - Implementation plan has been developed
  - Requirements documents are being prepared