Cable Conductor Design Criteria
Tentative limits for current density

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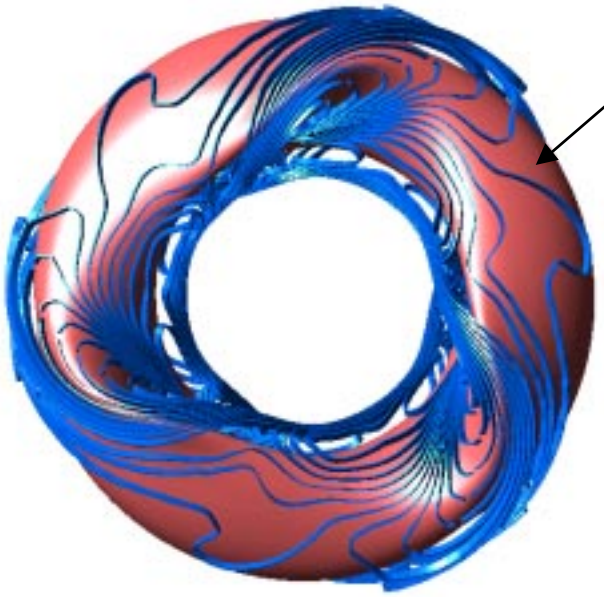
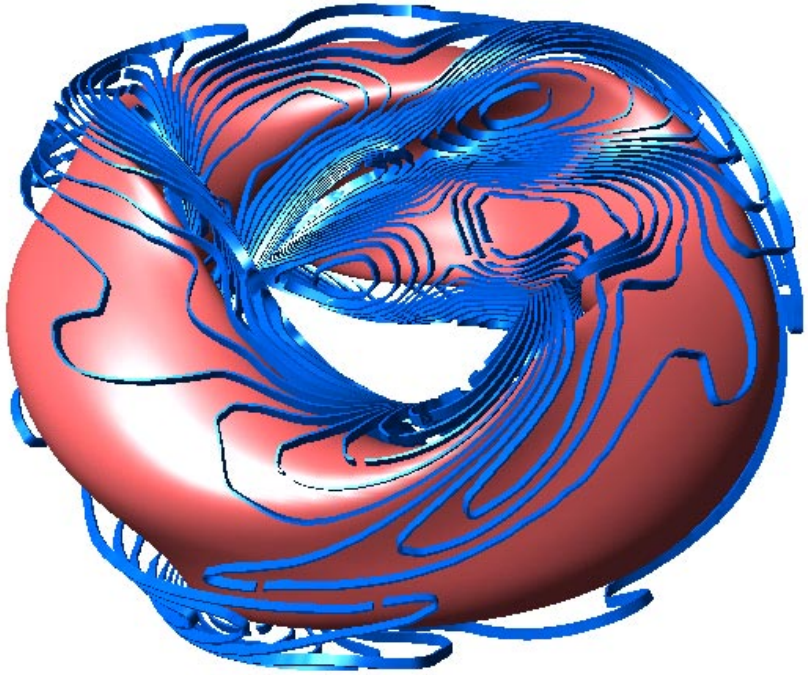
Presentation Outline

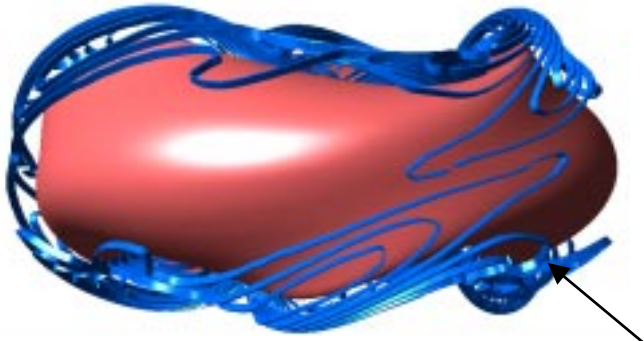
- Why are we using cable conductor?
- What might limit the current density?
  - max temperature at end of pulse
  - thermal stress due to temperature rise
  - power consumption
  - cooldown and rep rate
  - fatigue
  - other
- What is left to do (R&D status)?

Saddle Coil Design - typical winding



C10A Plasma

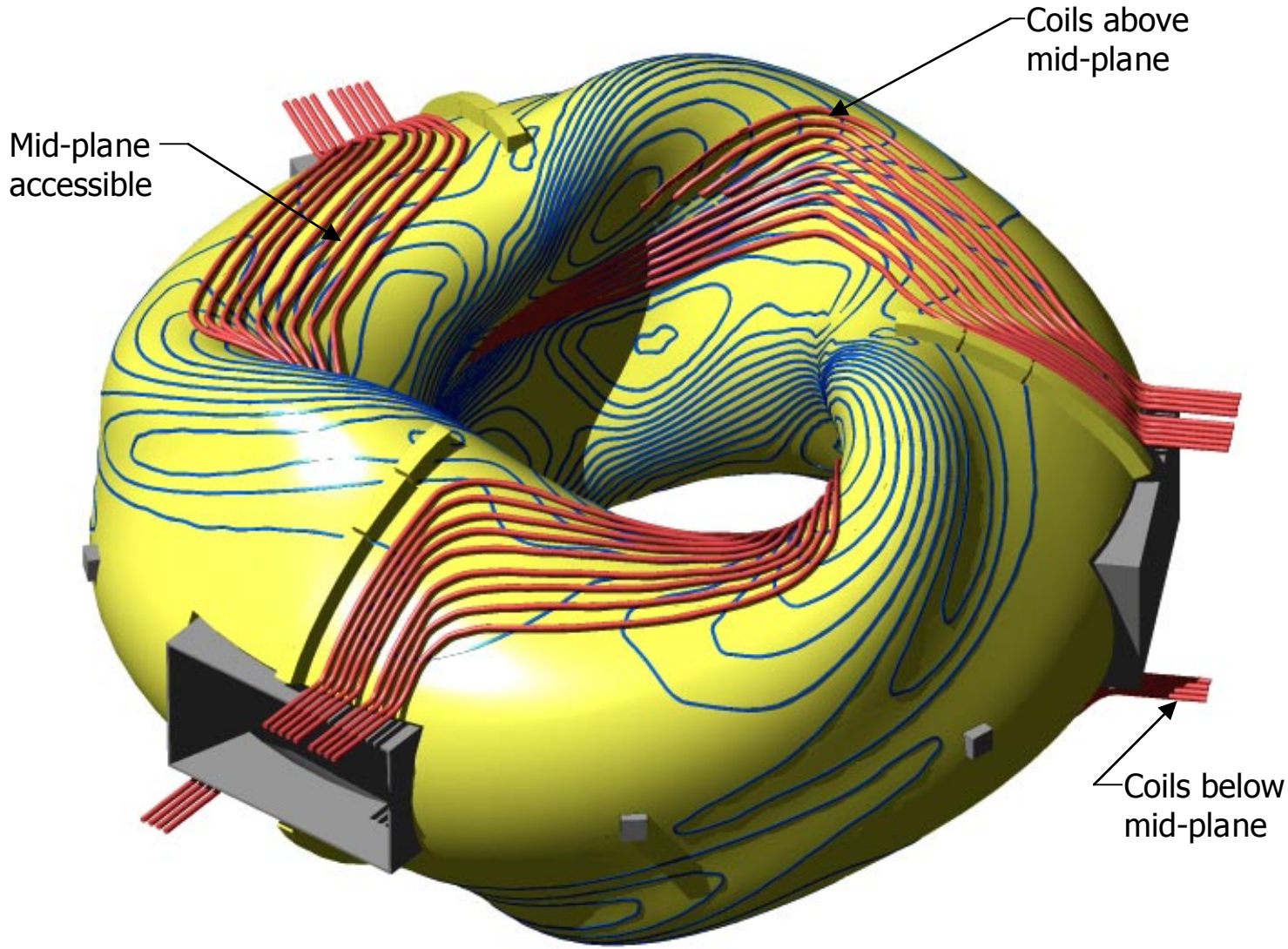




SAD185-16 Coilset

Dist from Plasma to Coil	18-cm
Longest Coil Length (1-turn)	16.7-m
Total Length of Conductor	4080-m
Total Weight of 78 Coils	6000-lb

Saddle coils are supported by contoured shell

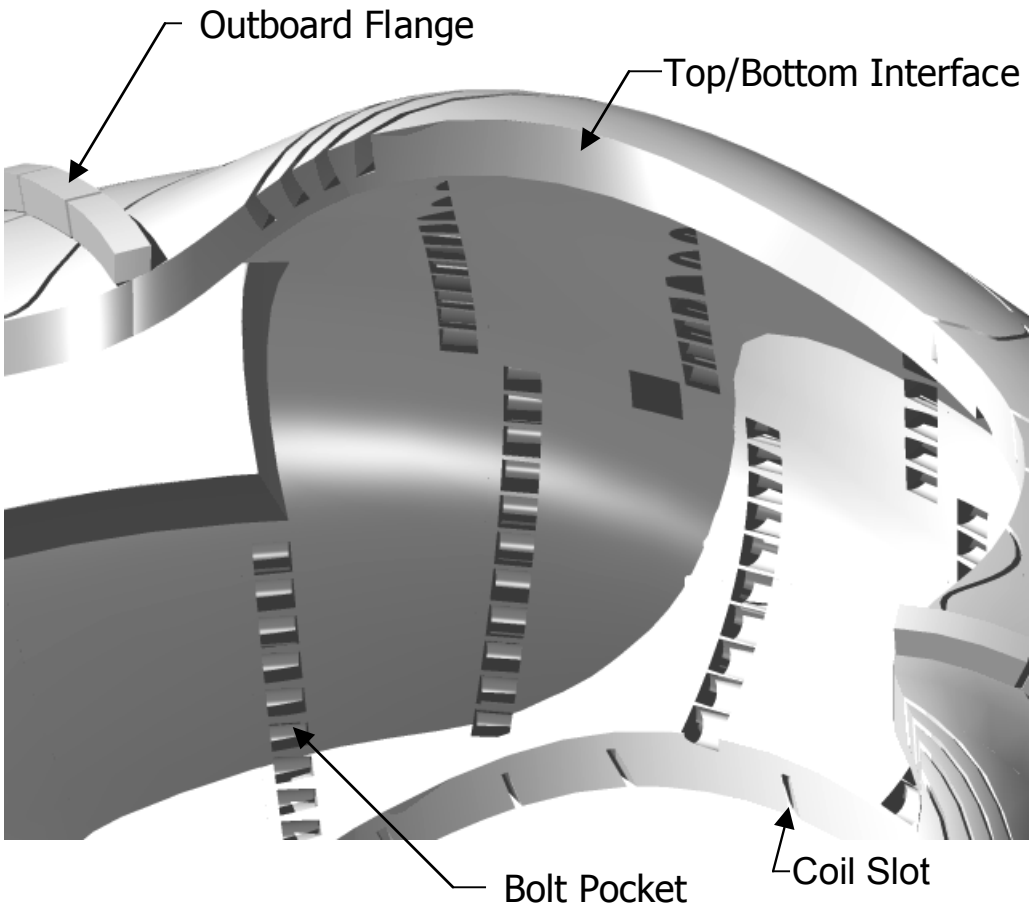


Shell winding structure is assembled with bolts

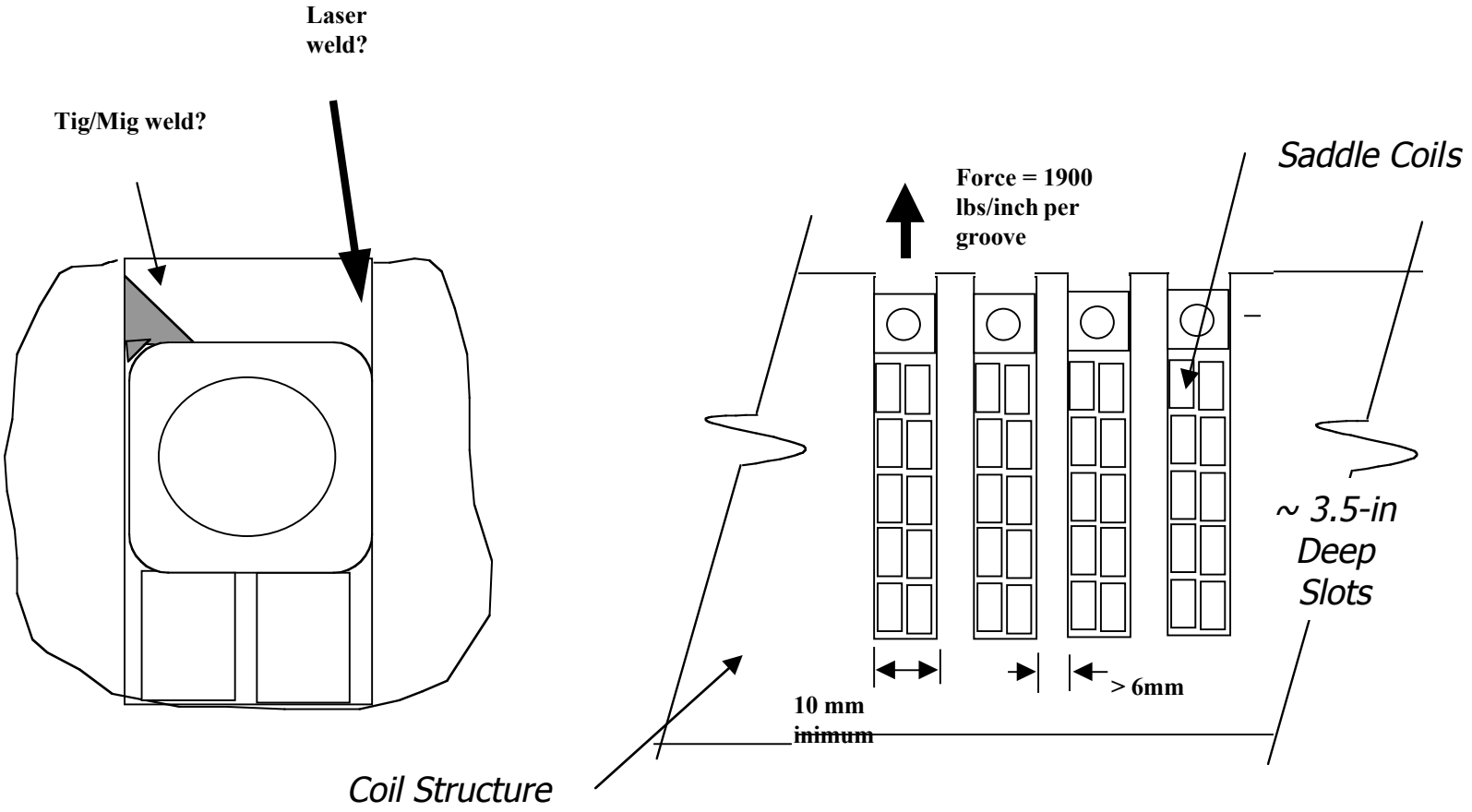
Inboard/outboard wedges attached by pocketed bolts
- Pockets formed in casting
- Machined through hole and back spot-face
- Left/right pockets give fewer patterns
- Feasible for up to 1-in dia bolt with 3-in spacing

Inner/outer subassemblies attached by pins at top and bottom
- Shop recommends flat and perpendicular surfaces on wedge ends for alignment

Outboard subassemblies attached by bolted flanges
- Three port locations have the fewest coil crossings



Conductor is located in narrow, closely spaced slots



Why did we choose cable over solid conductor?

- Advantages:
  - Winding flexibility
    - Grooves are too deep to wind conductor on conventional rotary table or with bending rollers
    - Solid conductor is too stiff to wind by hand
  - Reduced thermal stresses in shell for given temperature rise

- Disadvantages:
  - Effective packing fraction is low, current density in copper is high, increased temperature for given pulse length
  - Cooldown between shots is hard to quantify

Current density in Cu determines temperature rise

- Current density is a function of number of turns, packing fraction in braided conductor, insulation thickness, allowance for tolerance, ligament width, etc.

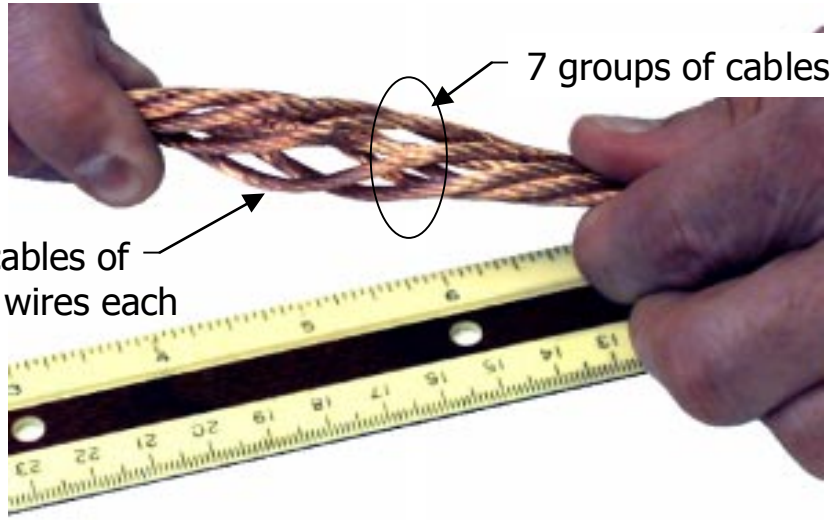
- For the original design (C10)
  - Number of turns per saddle coil = 10
  - Current density over gross total groove area ~8 kA/cm^2
  - Current density in copper **~17.5 kA/cm^2 at 2 T (~40%)**
  - Pulse length for 80 to 130 K rise = ~**1 second** (equiv square wave)
  - Power at end of pulse ~45 MW

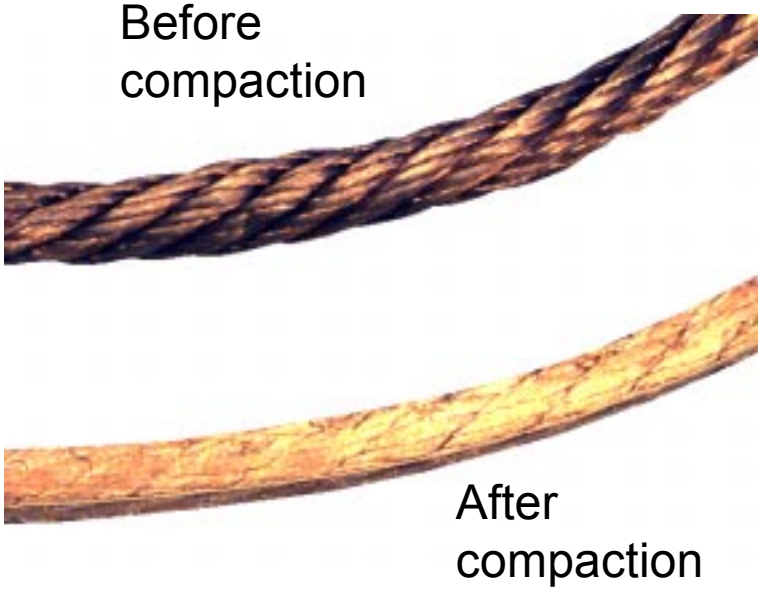
- More recent designs could have higher current density

Cable is compacted to rectangular shape

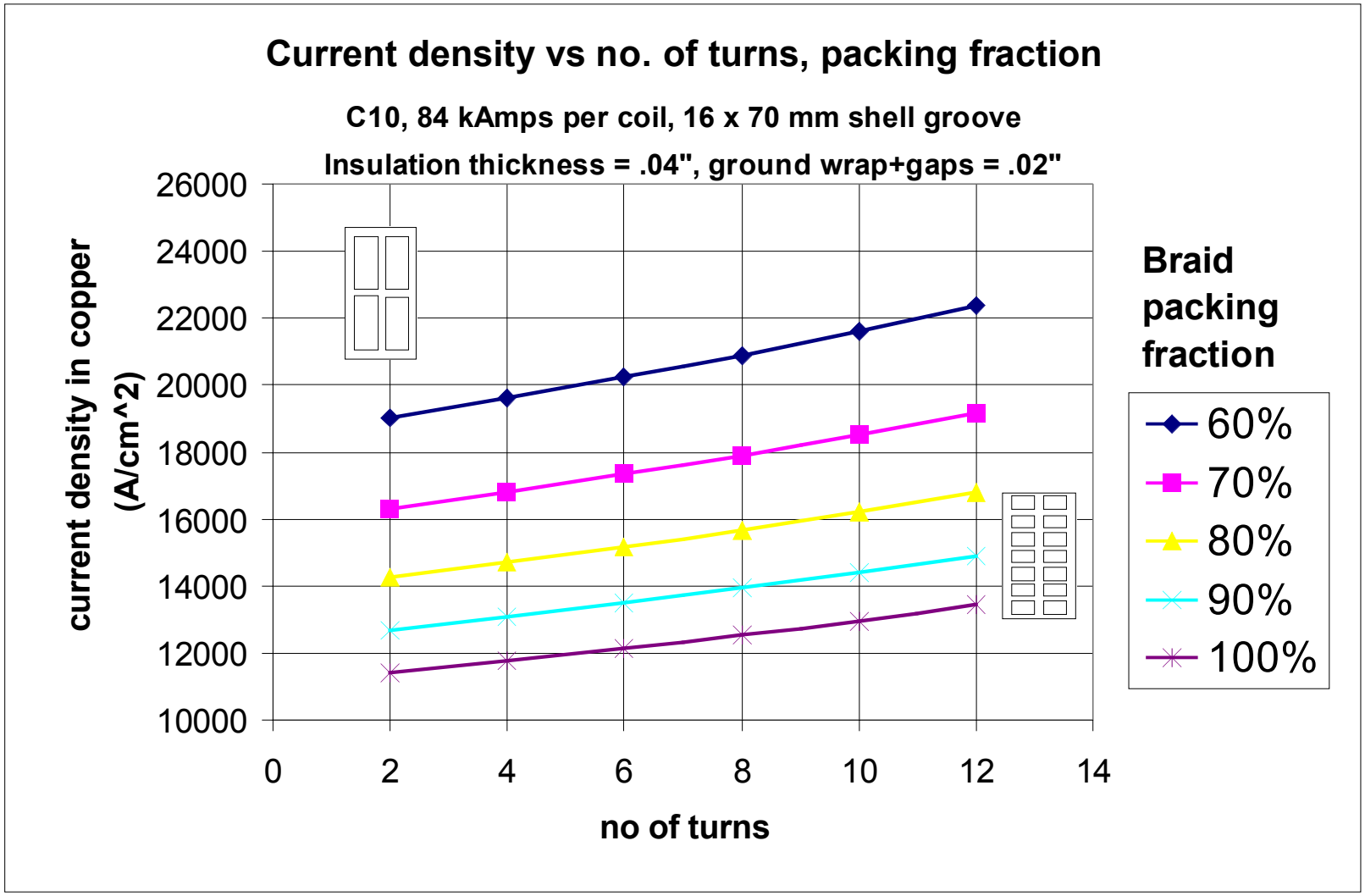
Two sample lengths of rectangular conductor have been prepared. The first was made in-house by pulling a 25-ft spool of 7x7x43/36 bare copper rope-lay cable through rollers to 0.218-in square (87% packing factor).

The second sample is a 1000-ft test run fabricated by New England Electric Wire Corp. It consists of a 5x5x48/36 bare copper rope-lay cable, squared off to 0.228-in and insulated with 0.0025-in Kapton tape, half-lapped.

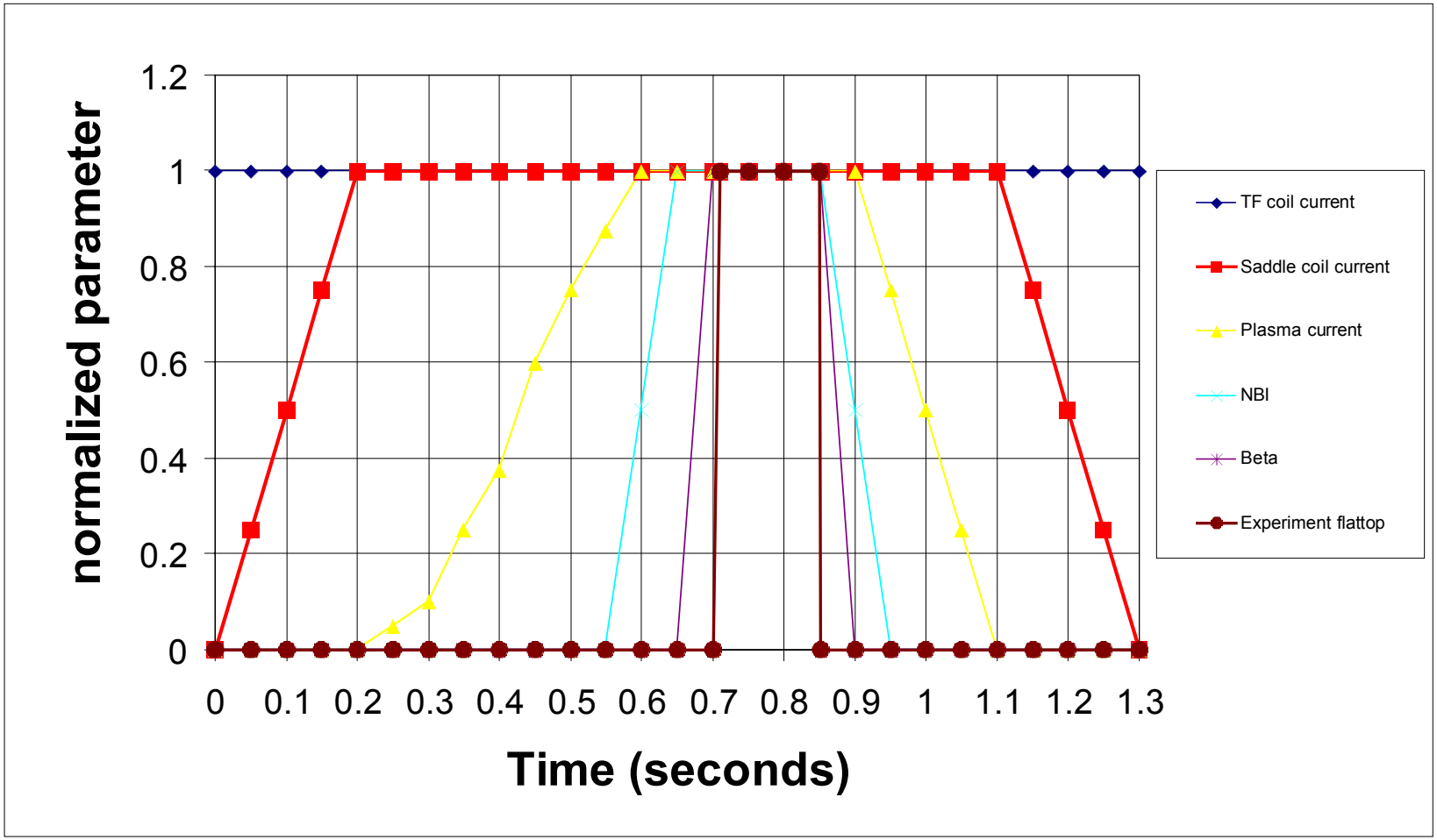




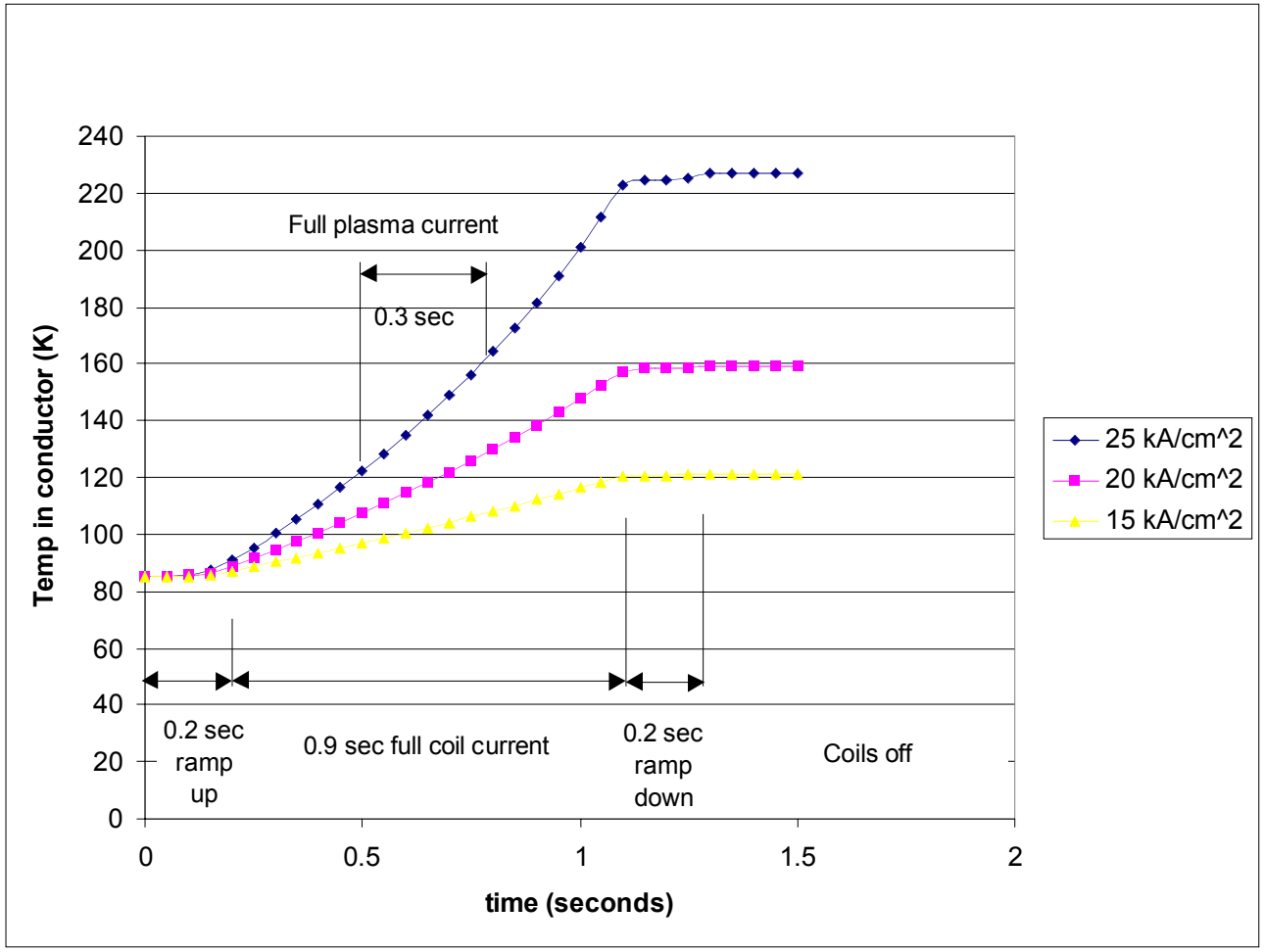
Current Density in Cu depends on winding details



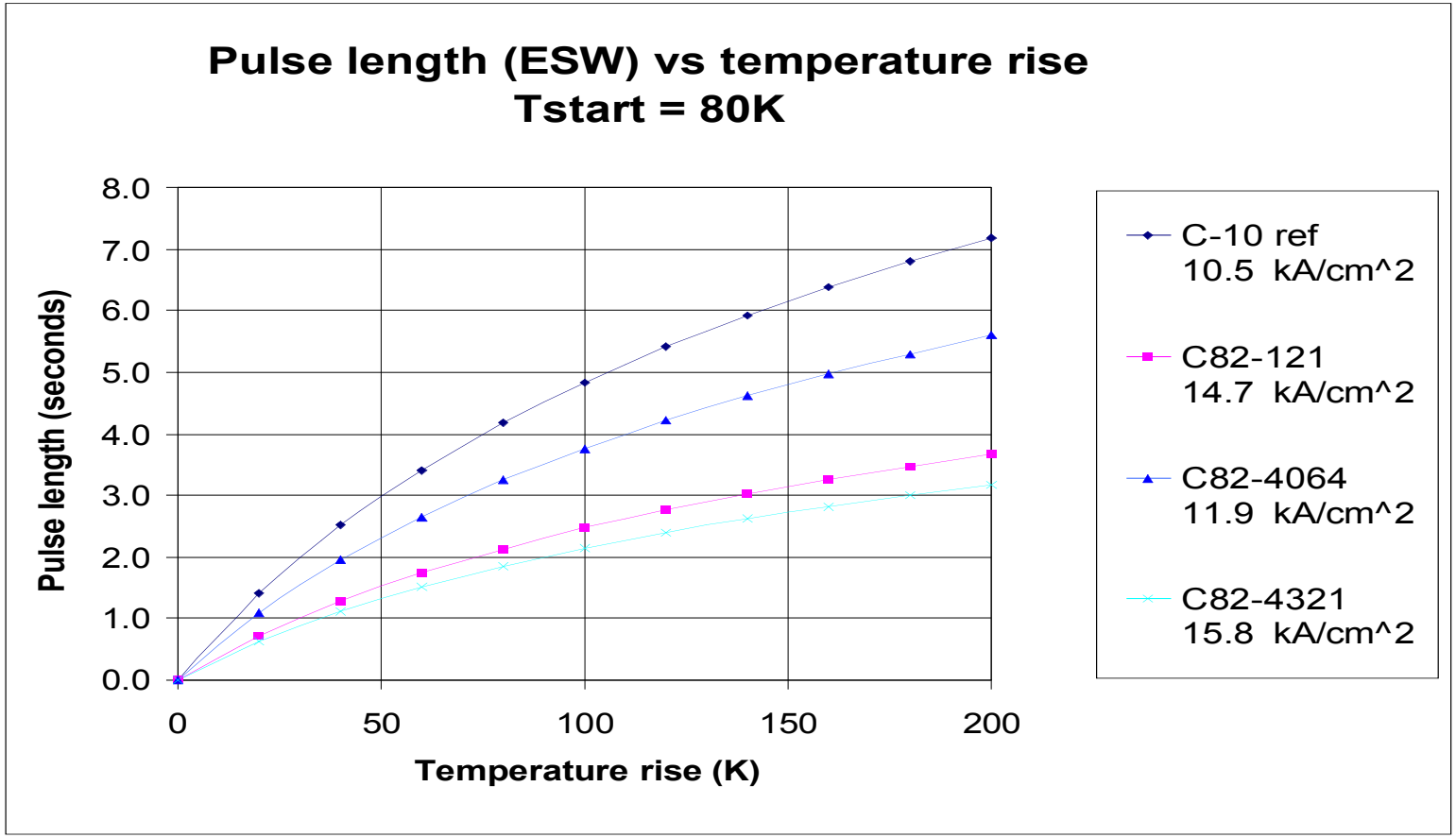
Ref. Scenario requires 1.03 second ESW in saddle coils



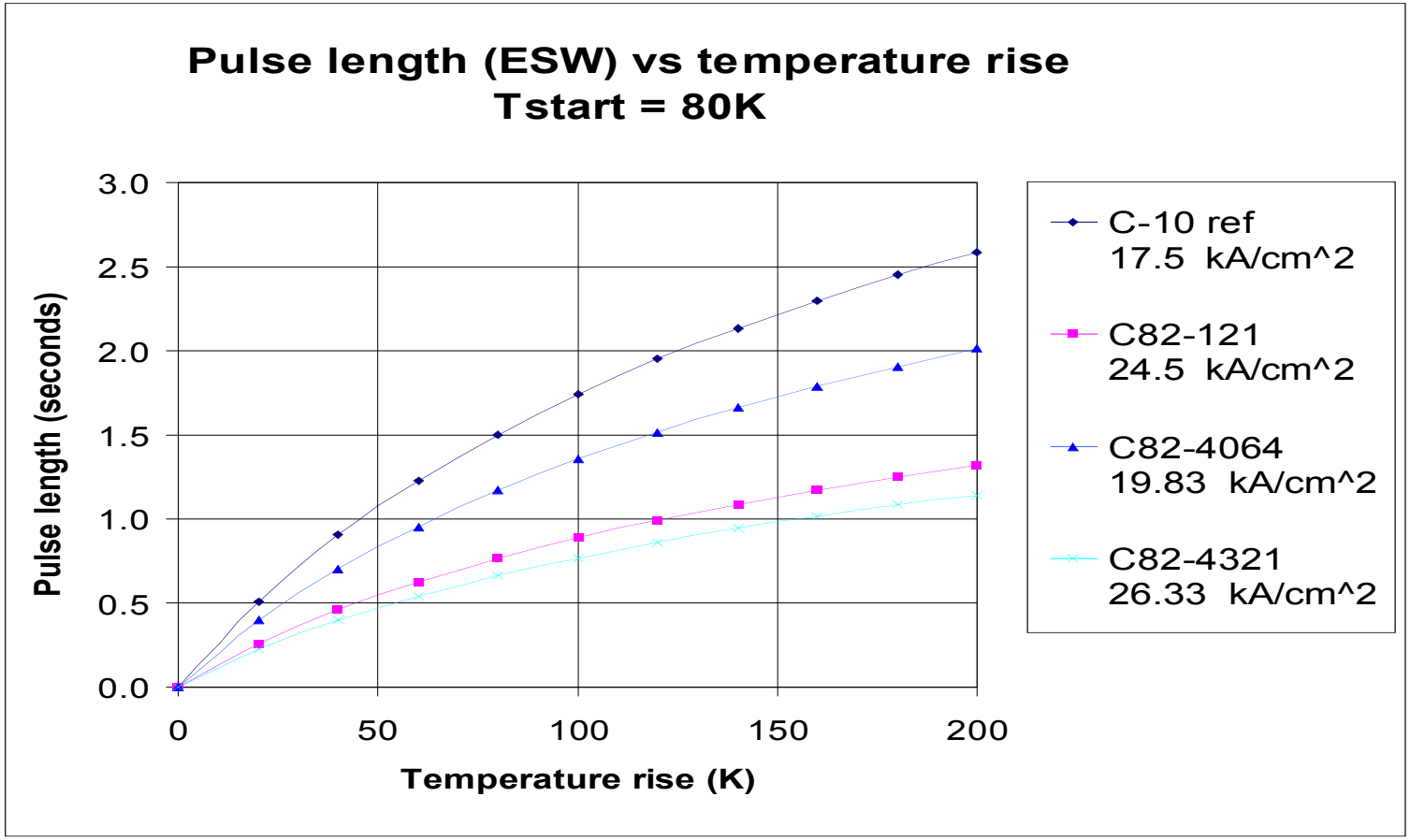
Temperature rise for reference pulse length



Coil Pulse Length : Some representative cases at 1.2 T



Coil Pulse Length : Some representative cases at 2.0 T

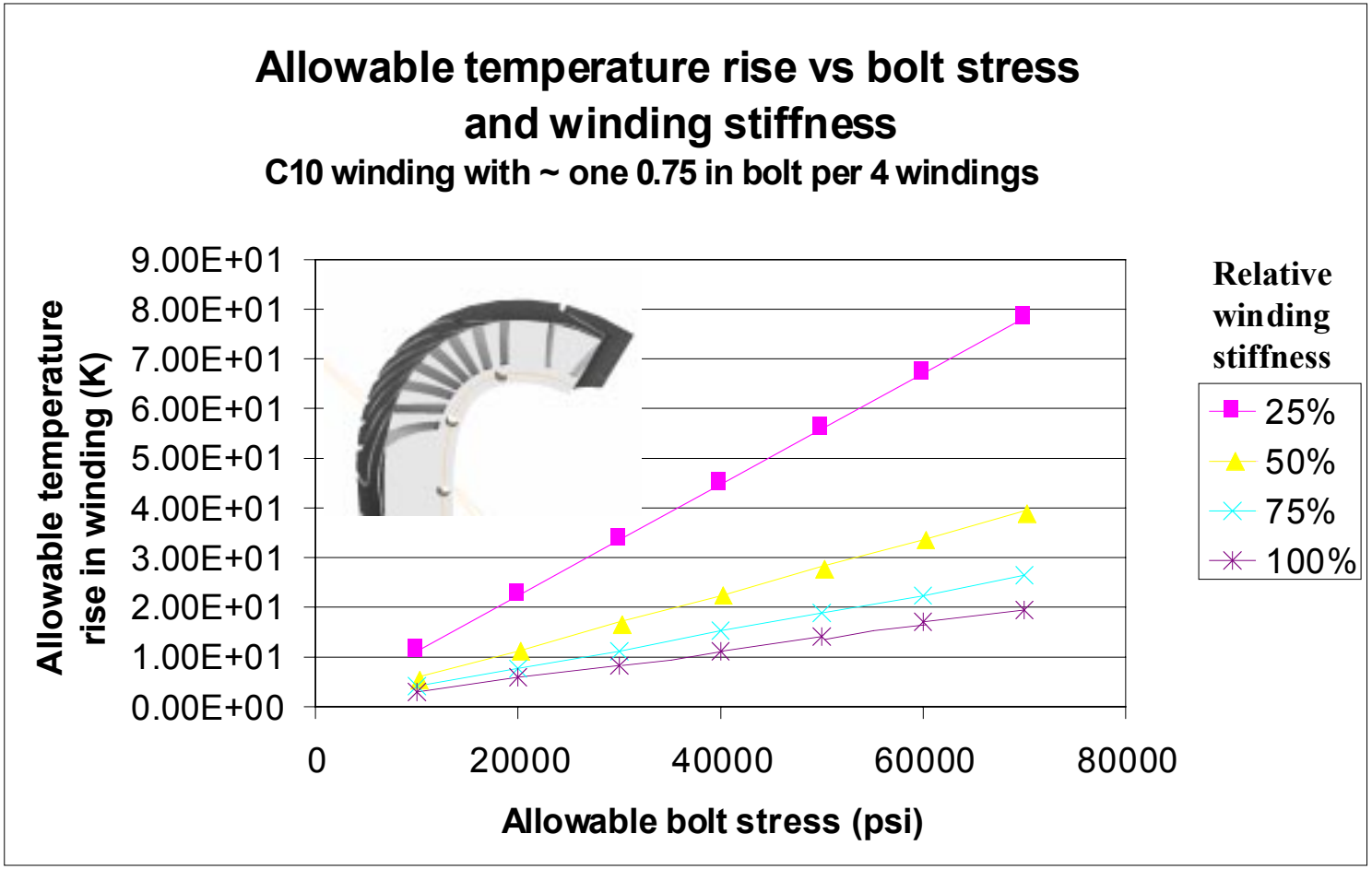


How hot is too hot?

- Primary limits for winding include:
  - Kapton insulation temperature limit ~150C
  - Epoxy potting temperature limit ~100C

- Secondary limits include:
  - Thermal stress in shell
  - Thermal stress in insulation
  - Peak power requirements
  - Peak voltage limits
  - Cooldown time after pulse
  - Fatigue life

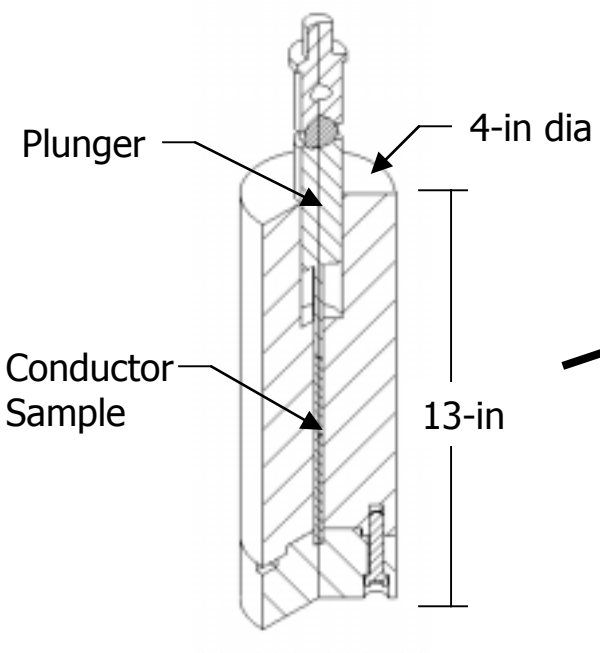
Thermal stress in shell bolts vs temperature show benefit of reduced winding stiffness

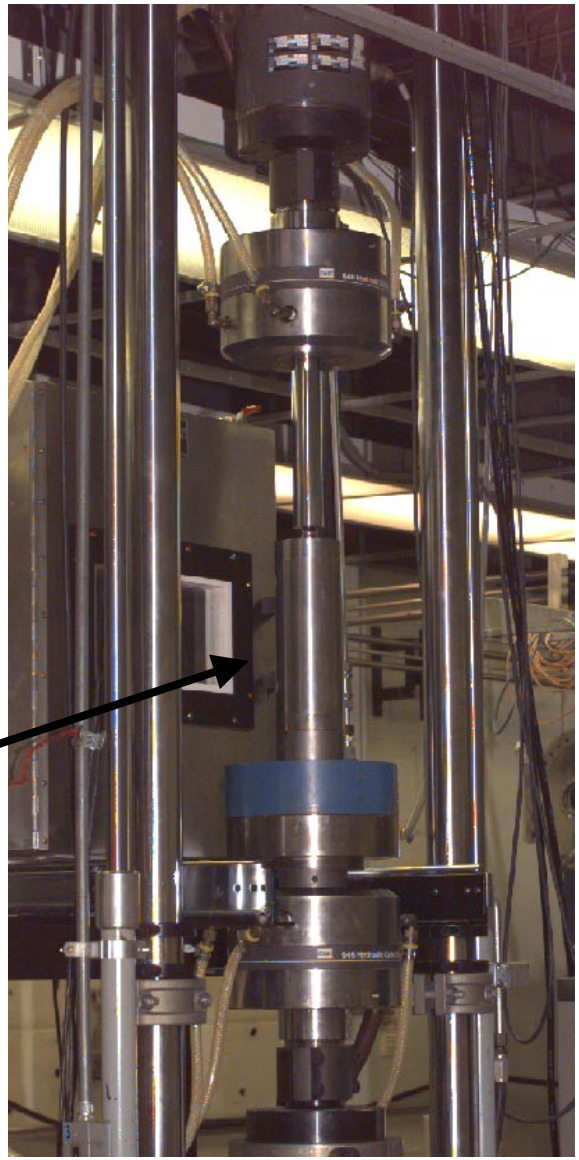


Fixture built to test cable stiffness in compression

Goal
- Establish stress-strain behavior of cable in rigid slot

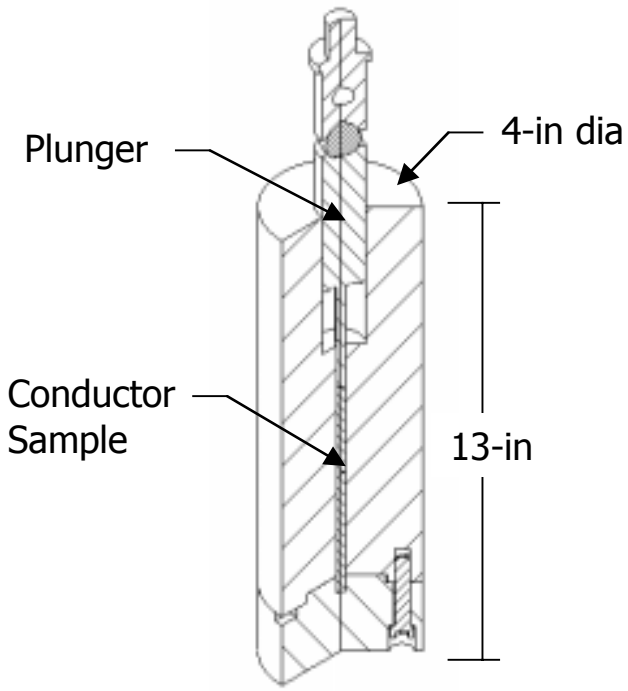
Status
- Fixture complete; tests complete

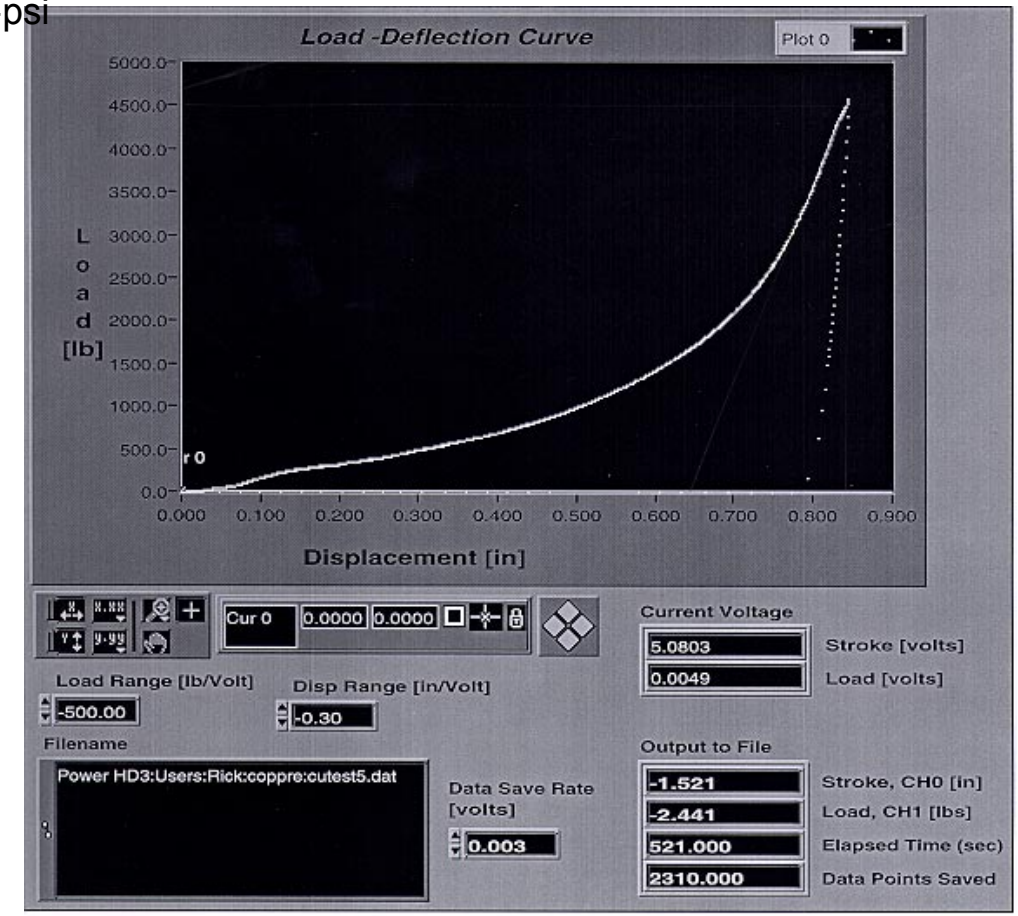




New England Wire Sample

- 5 x 5 x 48 Rope Lay Cable, 36-Ga Wire
- 0.0025-in Kapton Tape, Half-Lapped
- Initial Packing Factor in 0.25-in Dia Hole is 0.48
- Final Packing Factor is 0.85
- Effective Modulus at End of Test is 1.E6-psi

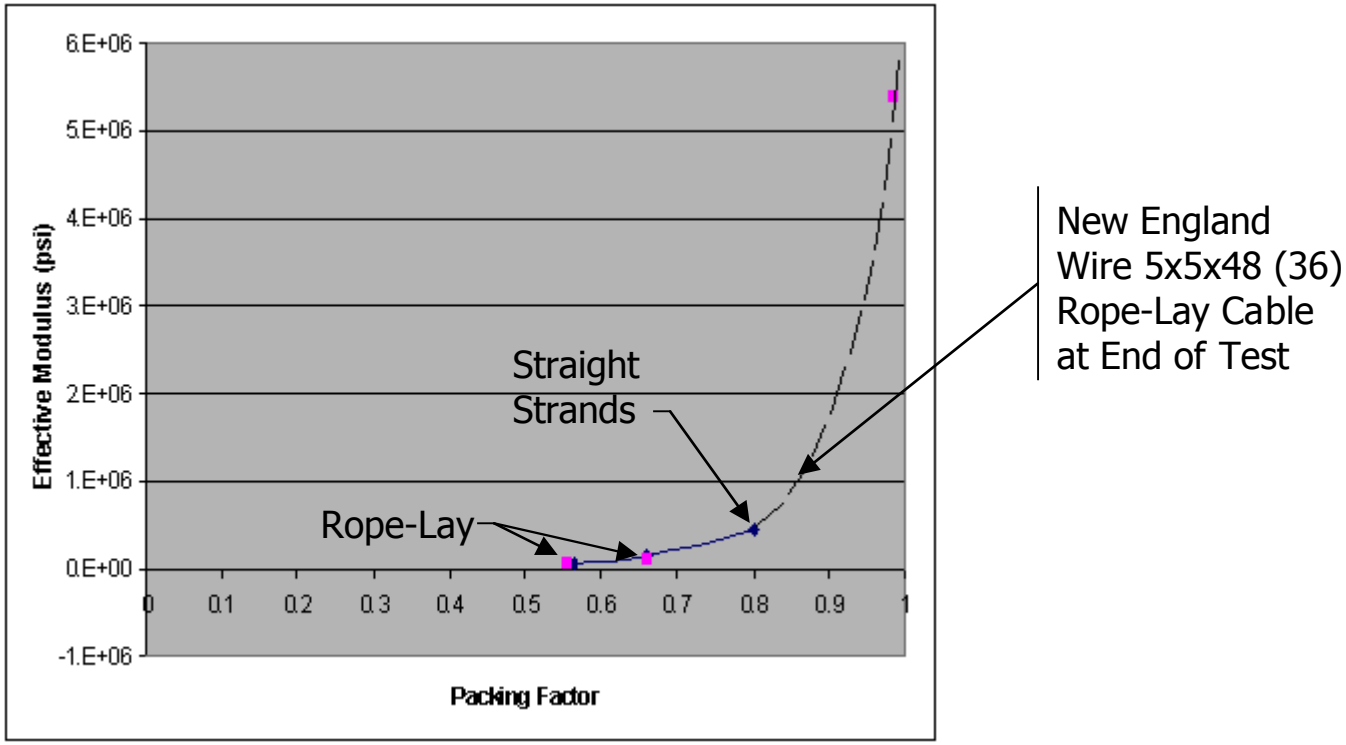




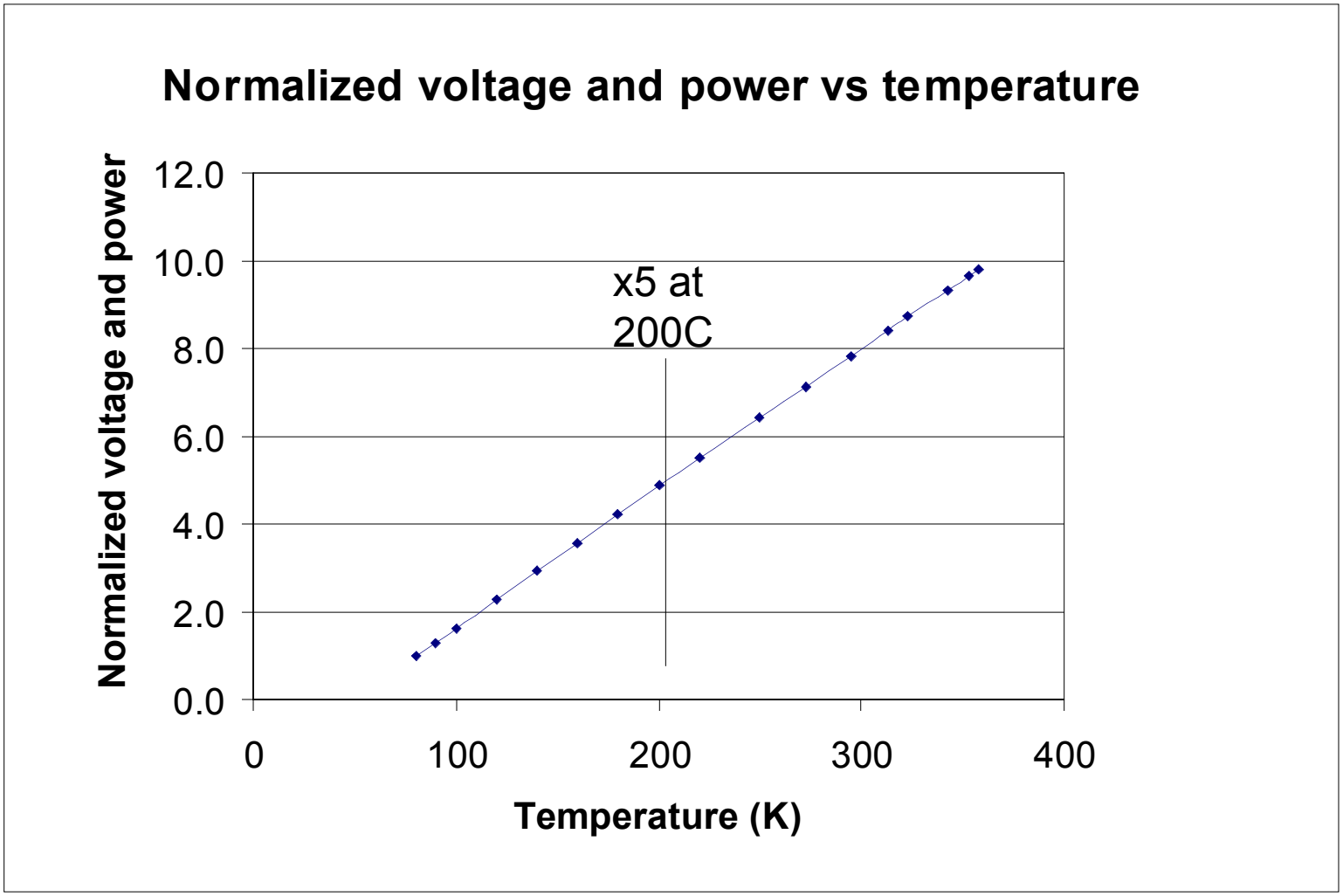
Compression Test Results

Flexible cable is soft in compression up to packing factor of ~90%

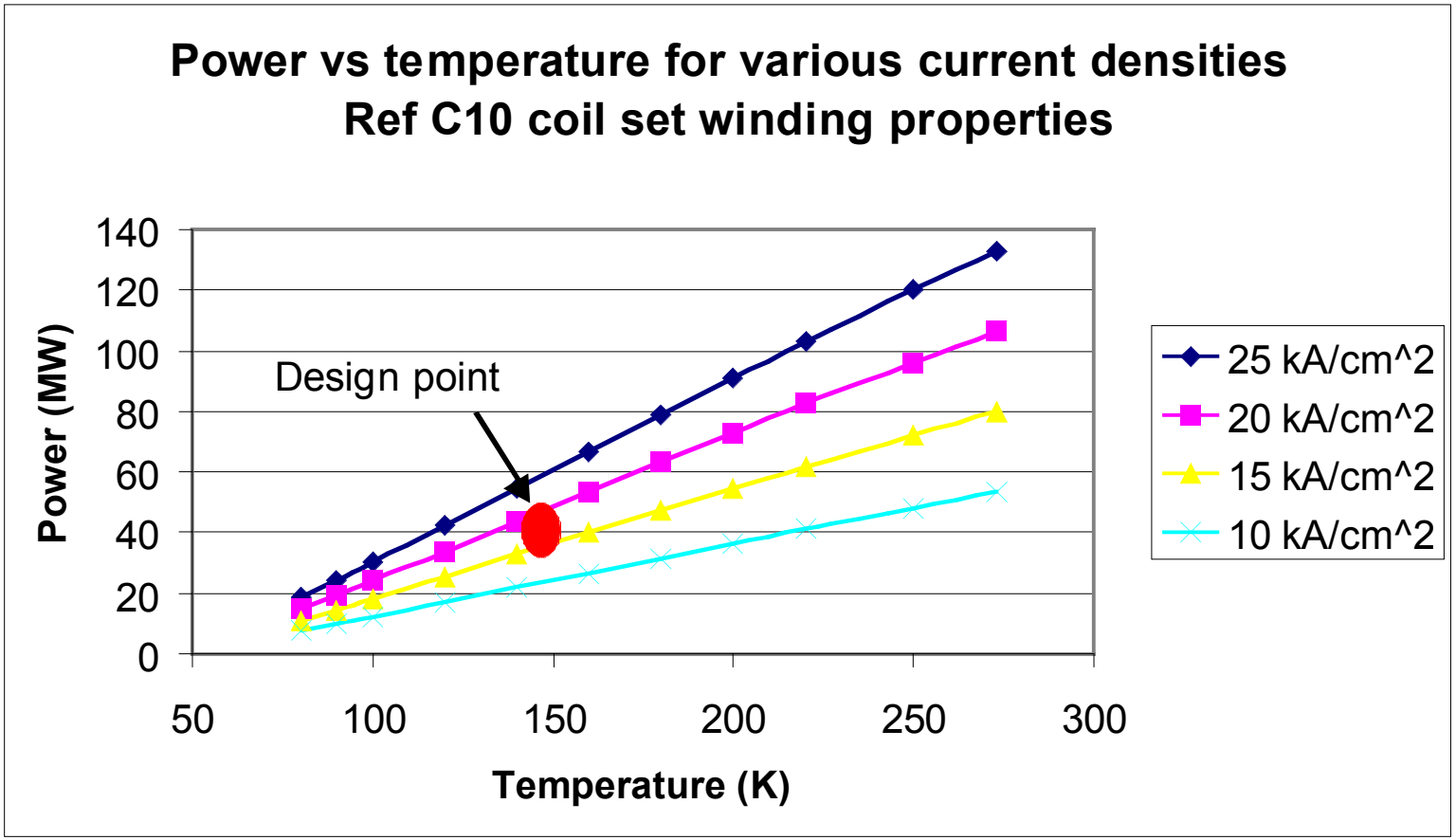
- Apparent modulus compared with volume packing factor
- Results indicate that cable stiffness is low at PF<1
- At predicted coil conditions (100-K temp rise, strain=.002, PF=0.75), load on conductor is minimal



Coil voltage / power proportional to Cu temperature

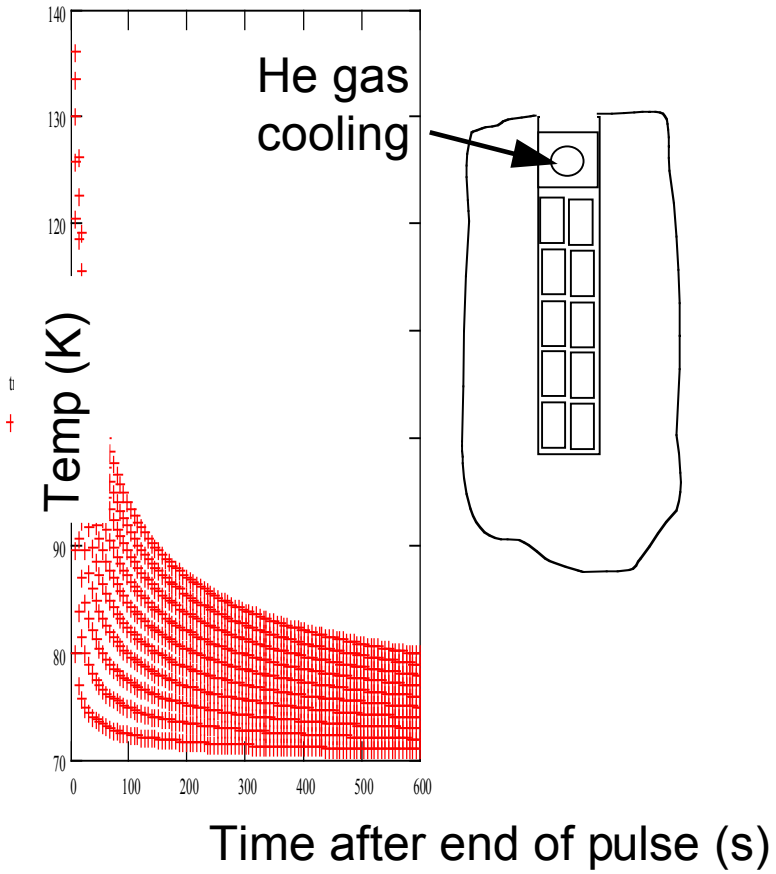


Coil power for original C10 design



Cooldown and rep rate

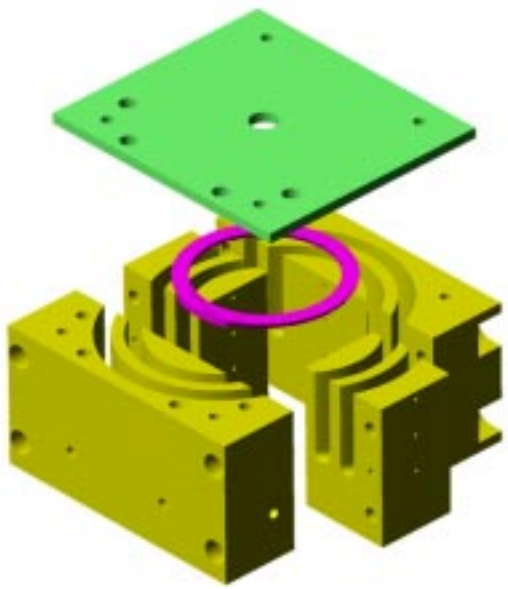
- Cooldown of conductor is a function of total energy input, coolant mass flow rate, thermal contact
- mass flow must increase to maintain cooldown time from higher temperature
- thermal contact may diminish with repeated, high temperature shots due to lateral compression

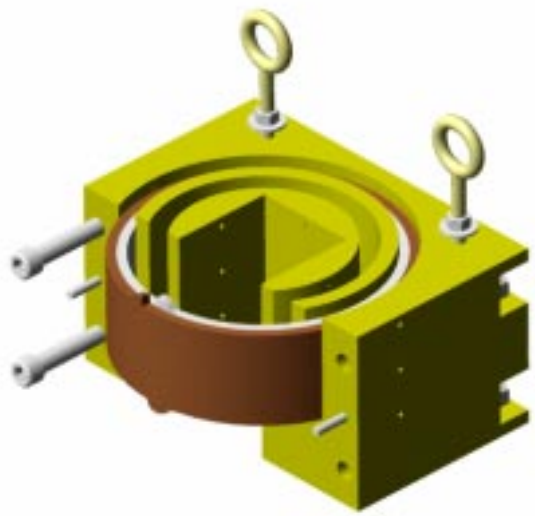


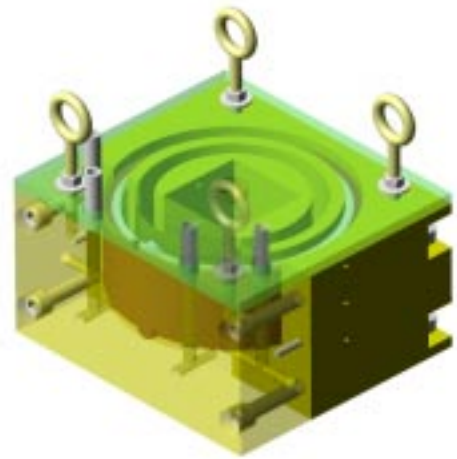
Winding/Thermal Cycle Test to investigate coil cool-down behavior during pulsed thermal cycles

Status

- Large Bronze winding form fabricated; conductor purchased
- Lexan block with deep slot being fabricated for potting tests
- Additional, smaller test article designed and ready for fab

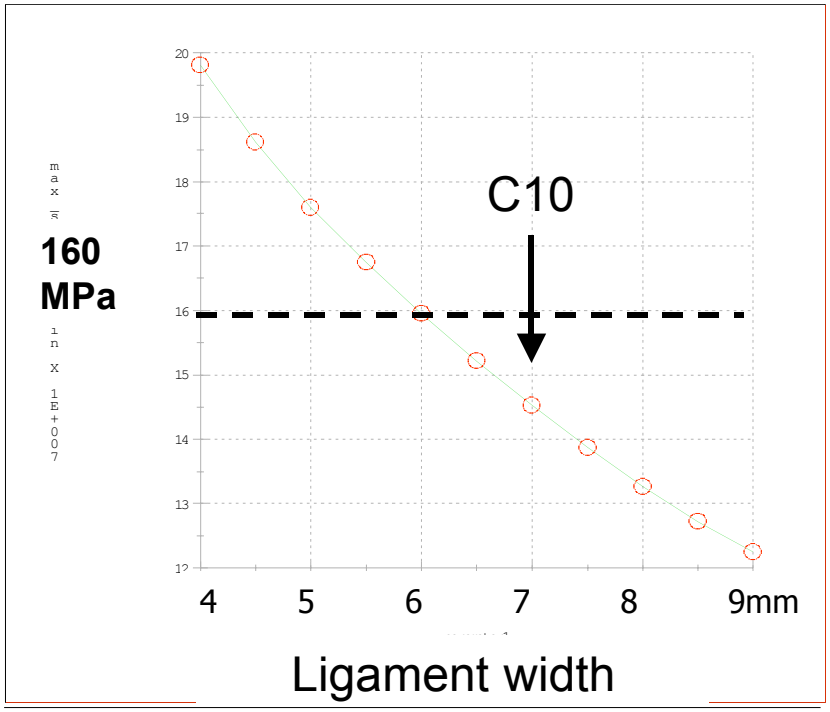


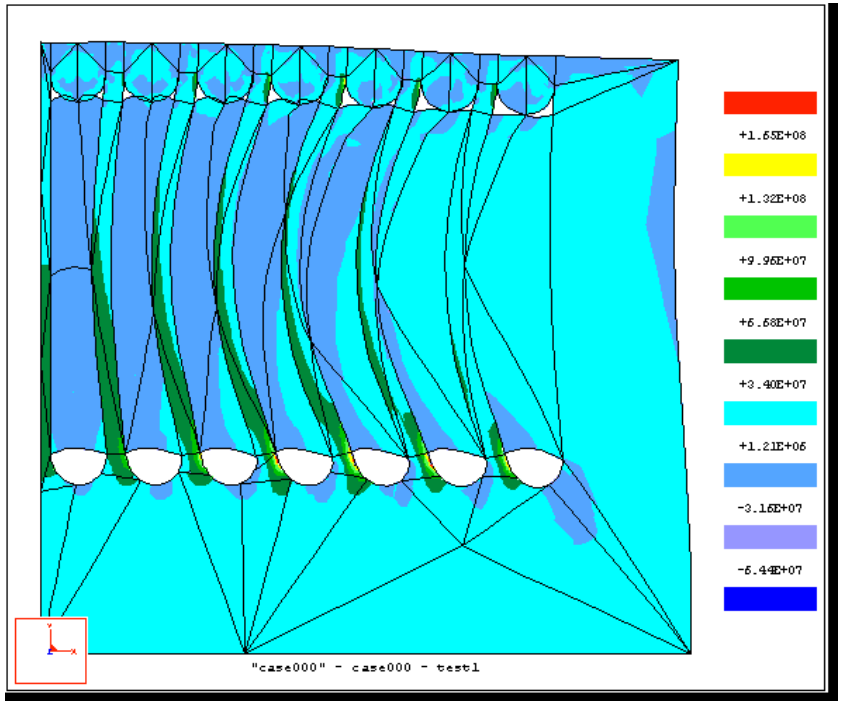




Ligaments between windings must react forces
Minimum ligament for C10 ~6 mm

- Conductor Modulus = 1-Gpa (test = 7 Gpa)
- Plasma Config C10-2T, Coil Set SAD185-16, Cut Thru One Half-Period





Recommendations

- **Lower current density is better**

- Temperature should be limited to < 180K (primarily power limit)

- Maximum current density must be less than
  - ~22 kA/cm^2 in Cu for 1.03 s ESW
  - ~9 kA/cm^2 over gross slot area

- Nominal current density should be lower (>20%) to allow for individual coils to vary for control and flexibility
  - ~18 kA/cm^2 in Cu
  - ~7 kA/cm^2 over gross slot area

- Ligaments between slots should be at least 6mm, more if current is higher (ie, fewer coils)

Summary

- Current density determines pulse length for adiabatic heating
- Current density is a function of number of turns, packing fraction in braided conductor, insulation thickness, allowance for tolerance, ligament width, etc.
- Reference scenario requires 0.7 second equivalent square wave (ESW) for saddle coil current (based on new physics requirement)
- Temperature is assumed limited to 180 K
- Maximum current density must be < 22 kA/cm^2 in copper
- Nominal current density should be < 7 kA/cm^2 over gross slot area