Cable Conductor Design Criteria

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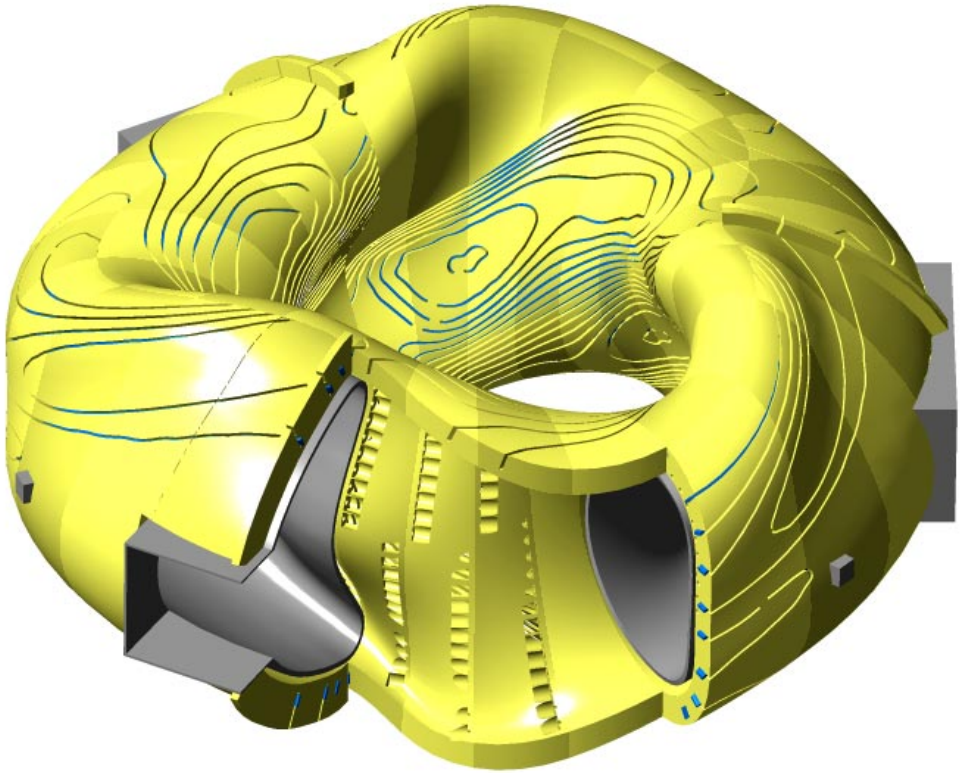
Presentation Outline

- What is basic saddle coil design?
- Why are we using cable conductor?
- What are design limits?
  - Current density
  - Bend radius
  - Minimum width of winding
  - Conductor spacing
- What is left to do (R&D status)?

Saddle coils are supported by contoured shell

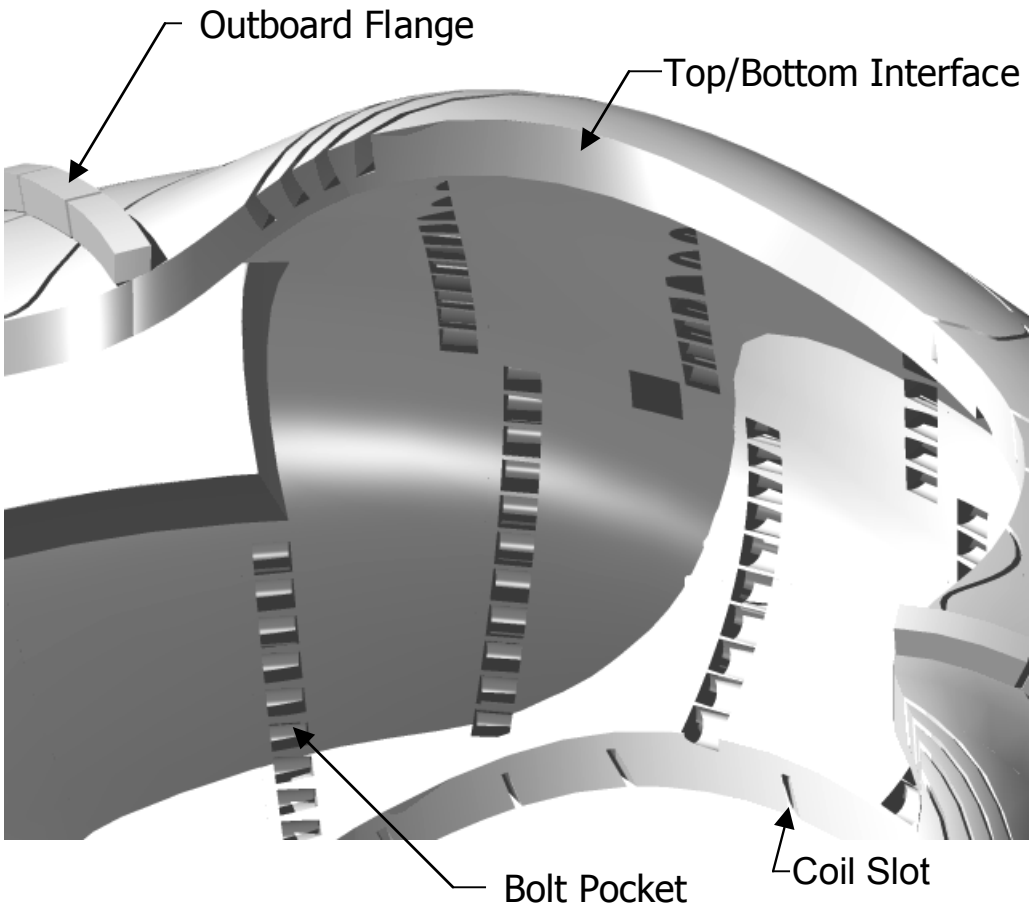


Shell winding structure is assembled with bolts

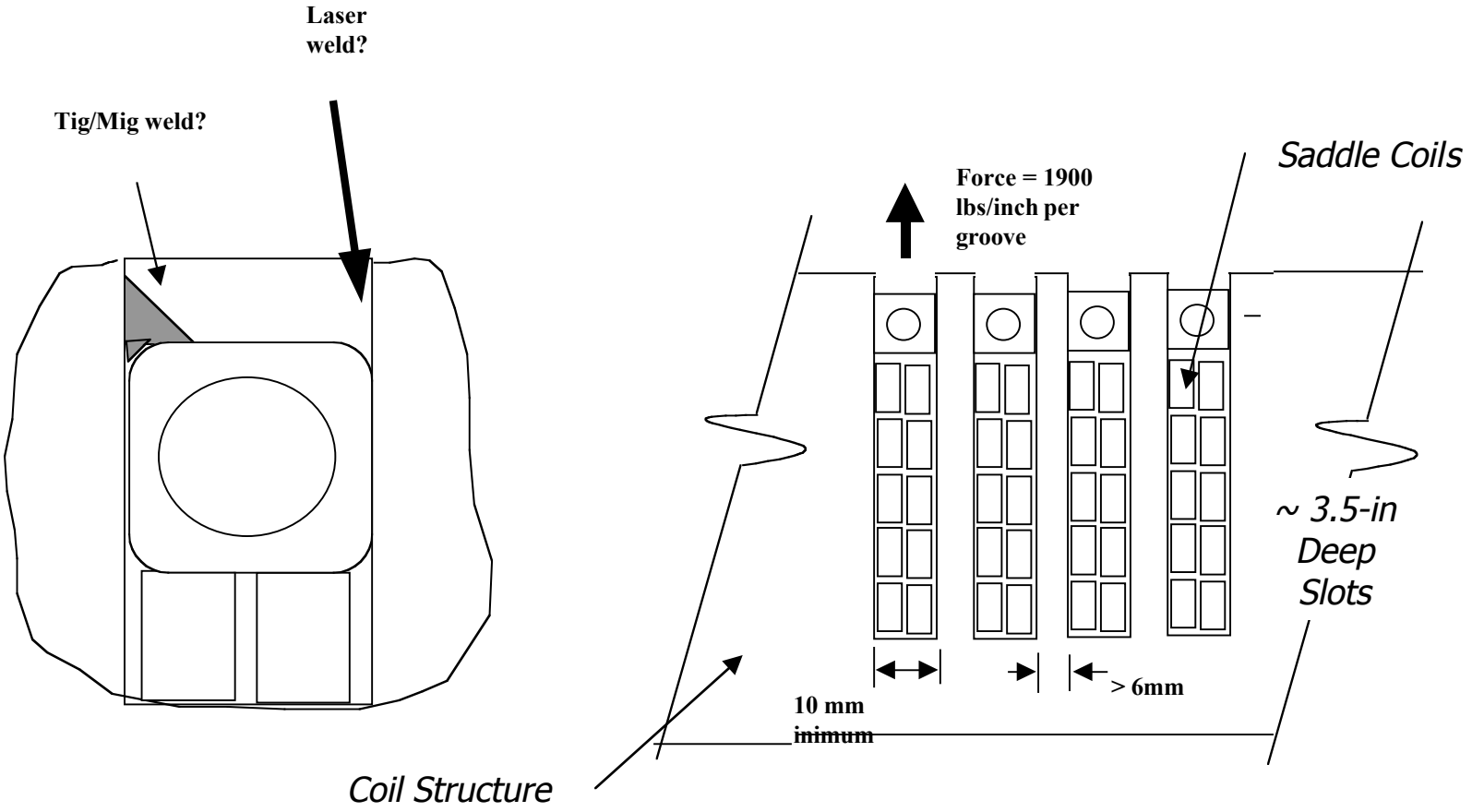
Inboard/outboard wedges attached by pocketed bolts
- Pockets formed in casting
- Machined through hole and back spot-face
- Left/right pockets give fewer patterns
- Feasible for up to 1-in dia bolt with 3-in spacing

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 is primary constraint

- The current density is limited by a number of factors

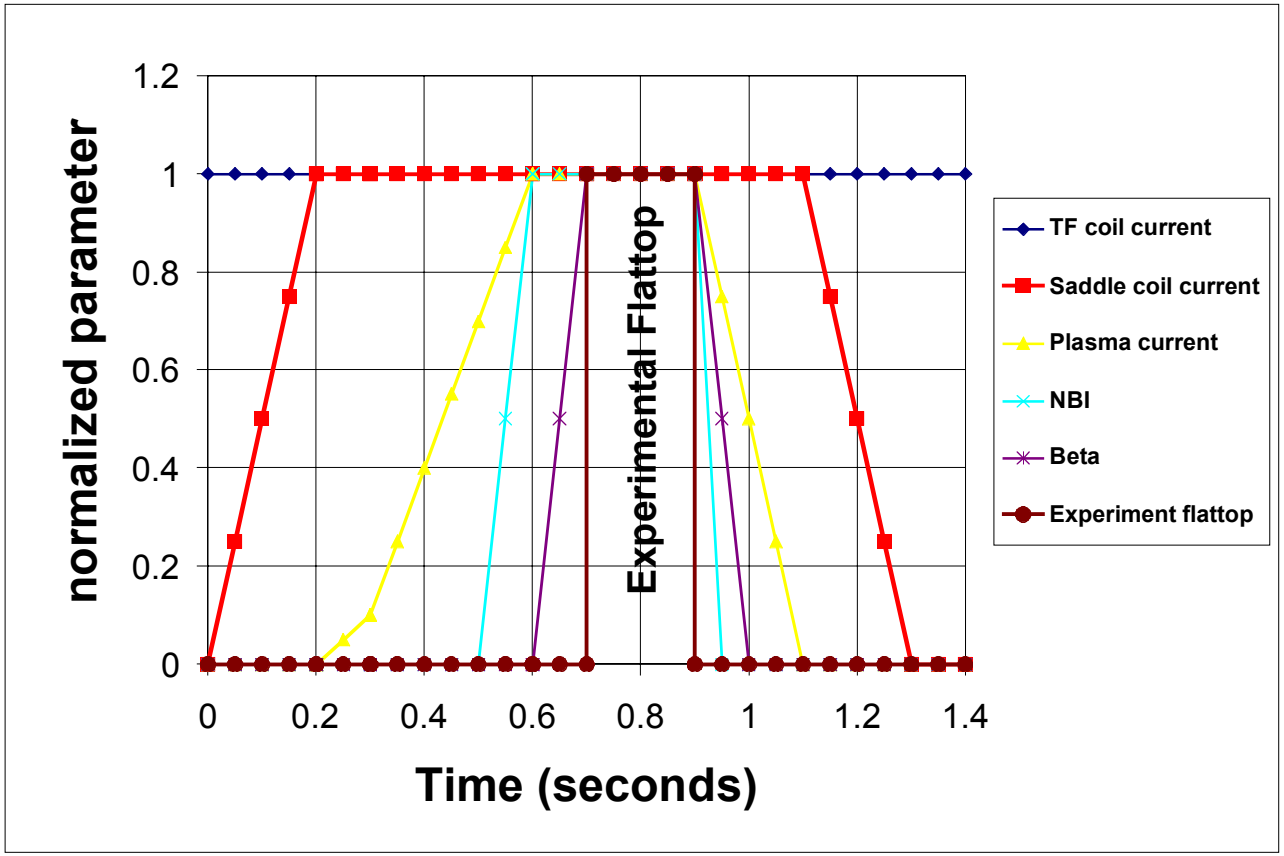
  - material temperature limits
  - thermal stress due to temperature rise
  - power consumption
  - cooldown and pulse repetition rate
  - fatigue, other effects

- The issues, then, are:

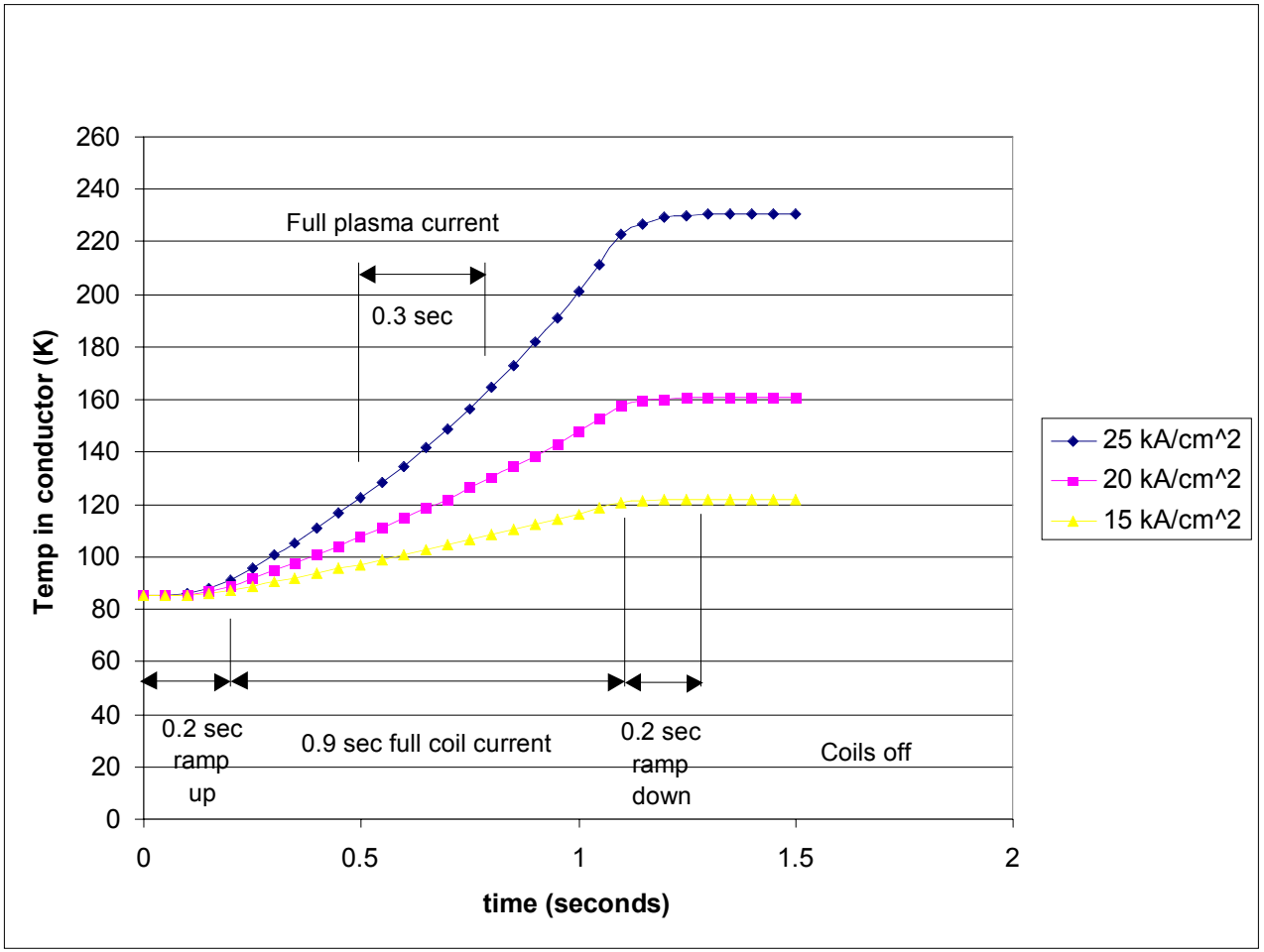
  - how hot does the conductor get during a pulse?
  - how hot can the conductor get before it reaches a limit?

How hot does the conductor get during a pulse?
Depends on pulse length

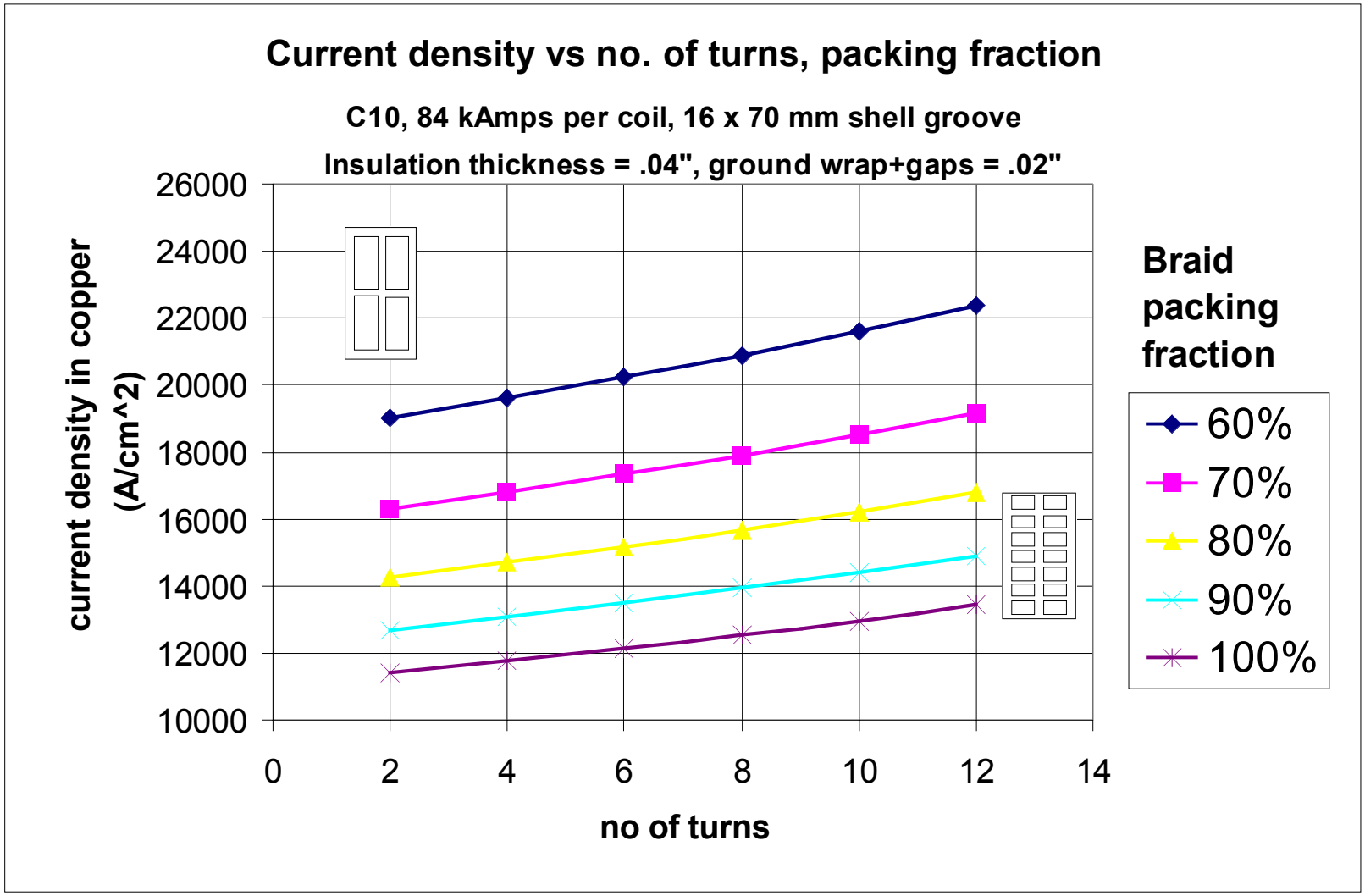
- Reference scenario at 2 Tesla requires 1.03 s ESW



How hot does the conductor get during a pulse?
Depends on current density in Cu



Current Density in Cu depends on winding details

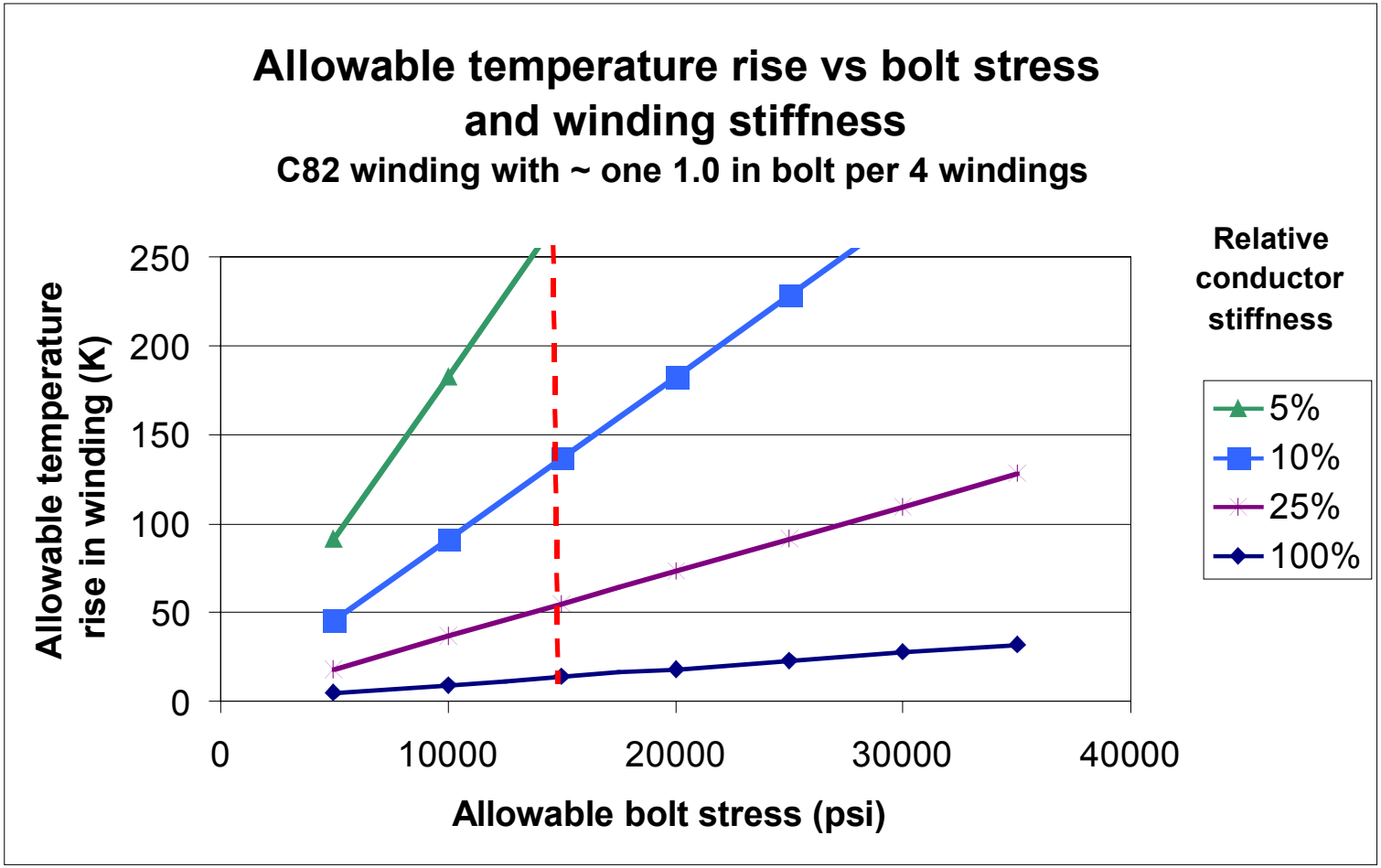


How hot is too hot?

- **Material temperature limits:**
  - Kapton insulation temperature limit ~260C (temp rise of 450K)
  - Epoxy potting temperature limit ~ 60C (temp rise of ~250K)

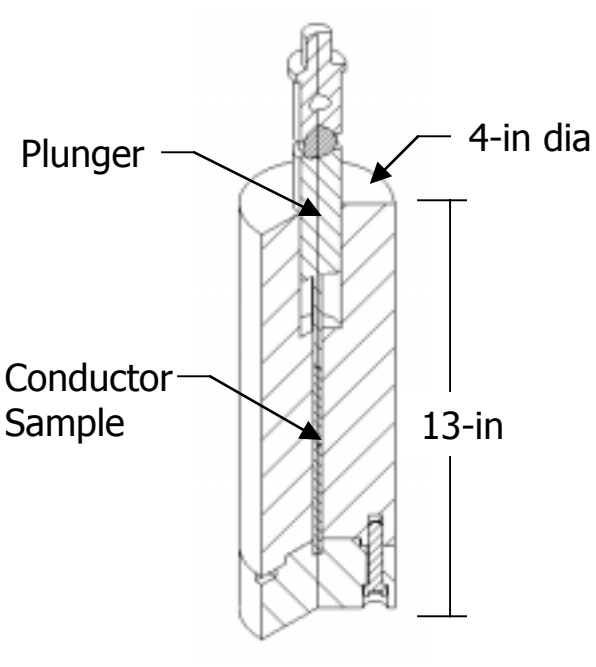
- **Thermal stress limits:**
  - Thermal stress in shell depends on winding spacing, bolt spacing and stiffness of winding
  - Temperature limit can be plotted as a function of bolt stress and winding stiffness
  - For 1 in. silicon bronze bolts, preload limited to 17000 pounds, magnetic load is 8500 pounds, thermal load must be less than 8500 pounds or 15 ksi
  - For typical winding, temperature limited to ~ 60C (temp rise~250C)

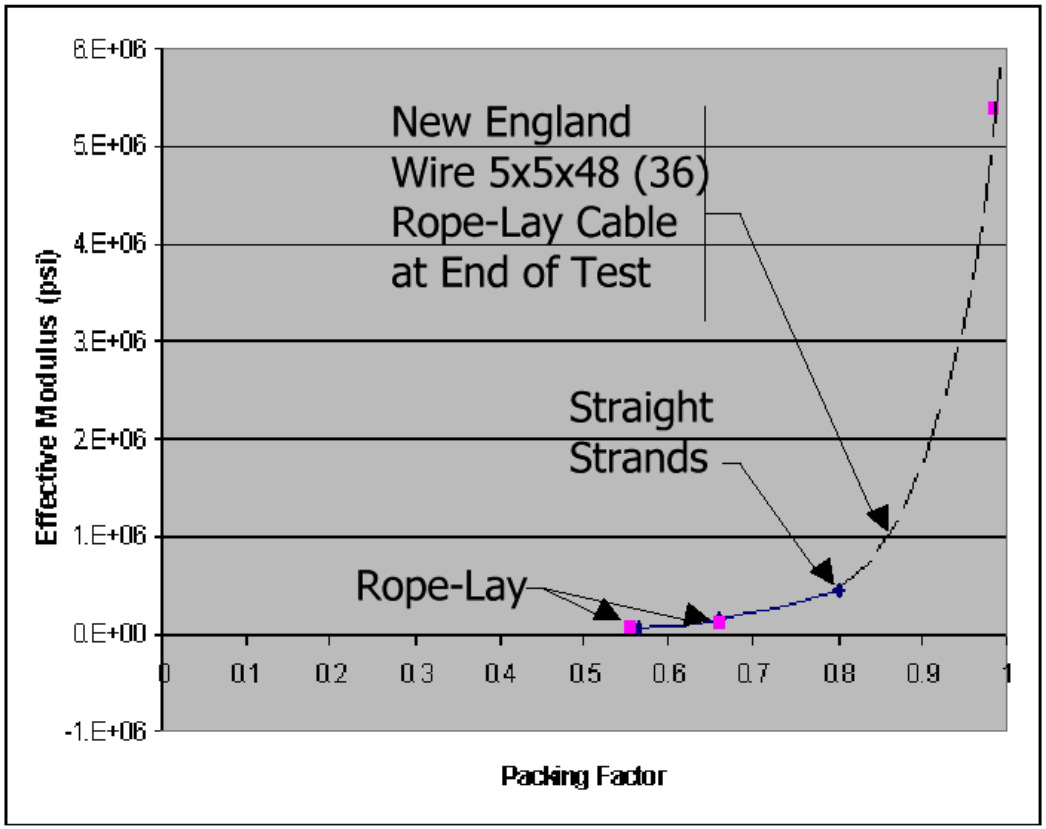
Thermal stress in shell bolts vs temperature shows dependence on winding stiffness



How stiff is the conductor?

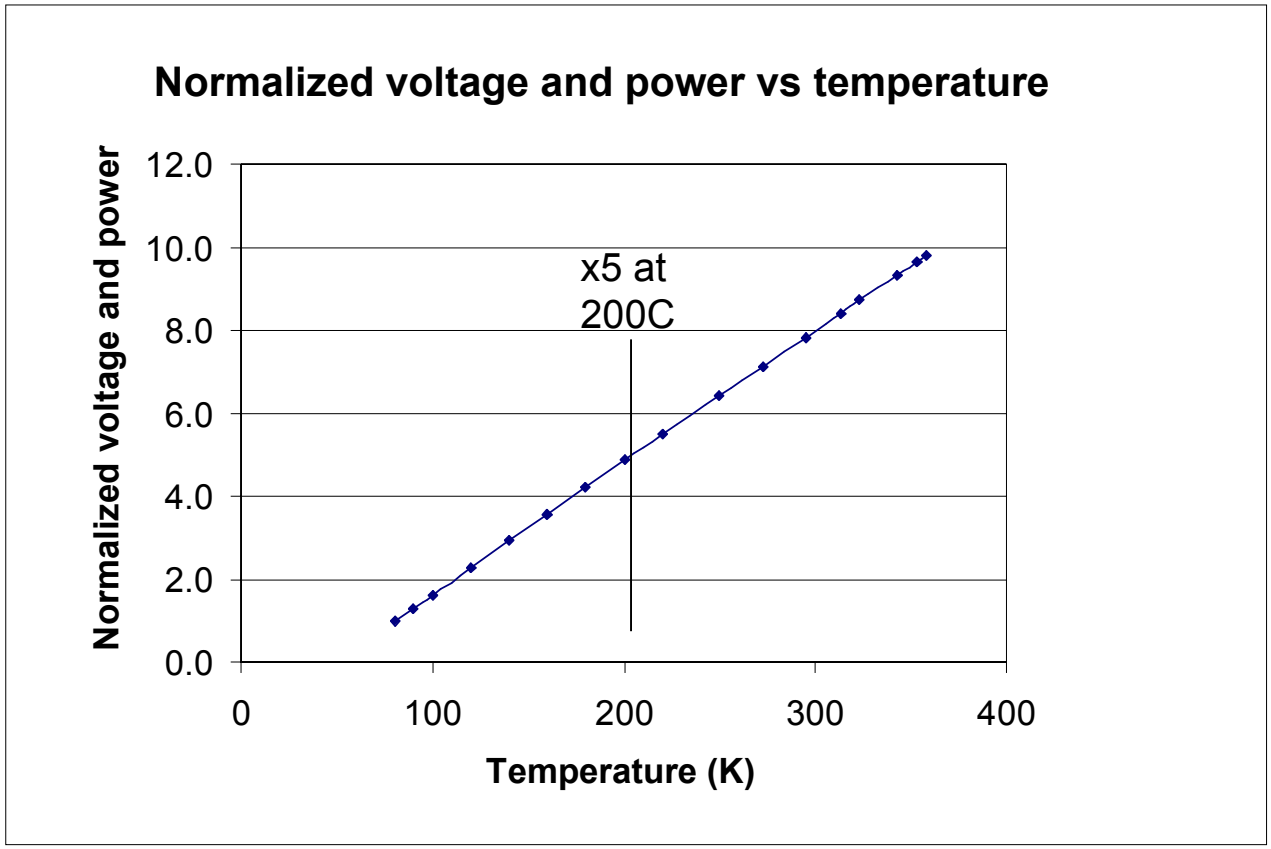
•Flexible cable is soft in compression up to packing factor of ~90%
•Compression modulus of 1e6 psi, (5% of solid) limits temperature to ~335K, or 250K rise



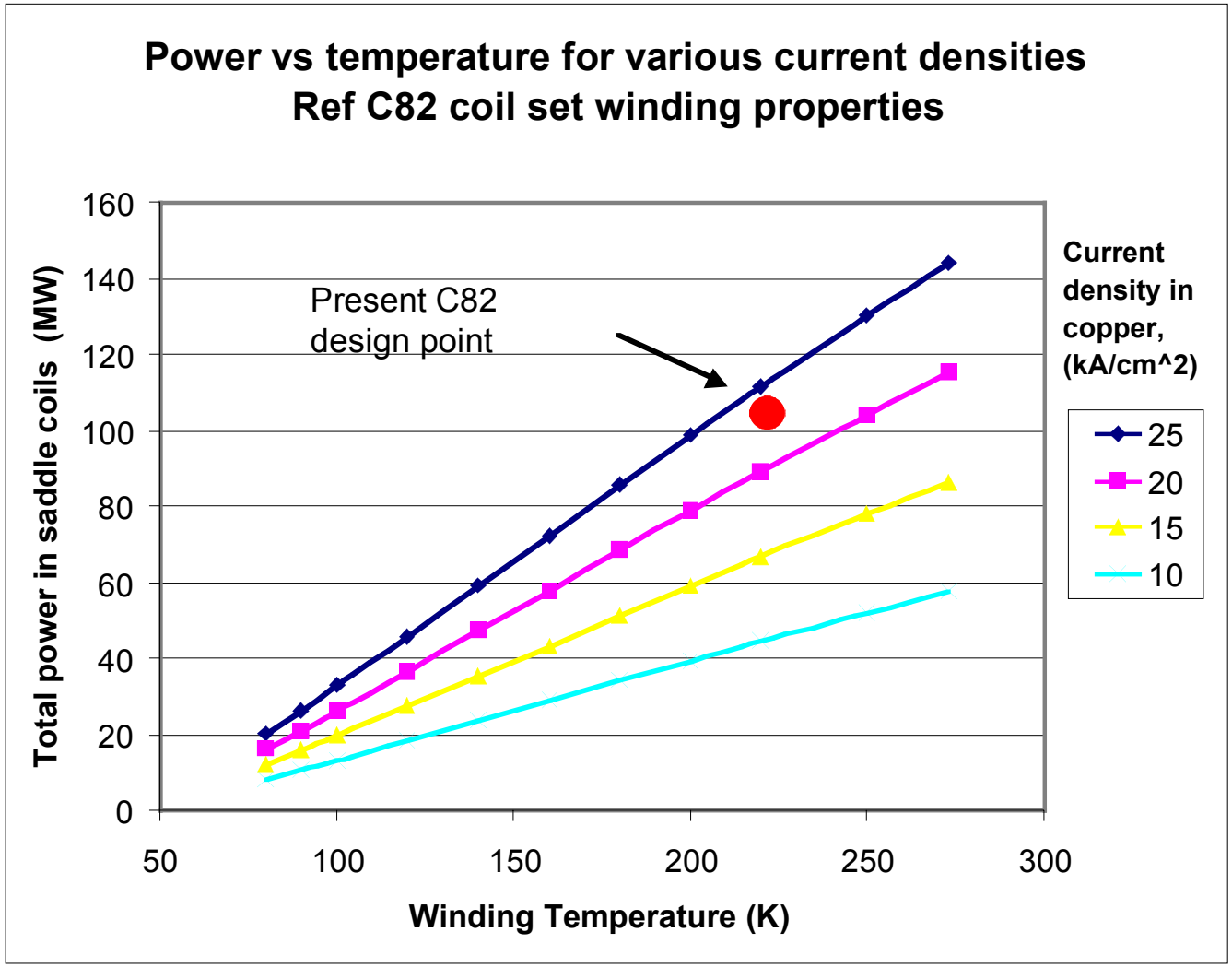


What about power consumption?

- **Power Consumption rises sharply with temperature:**

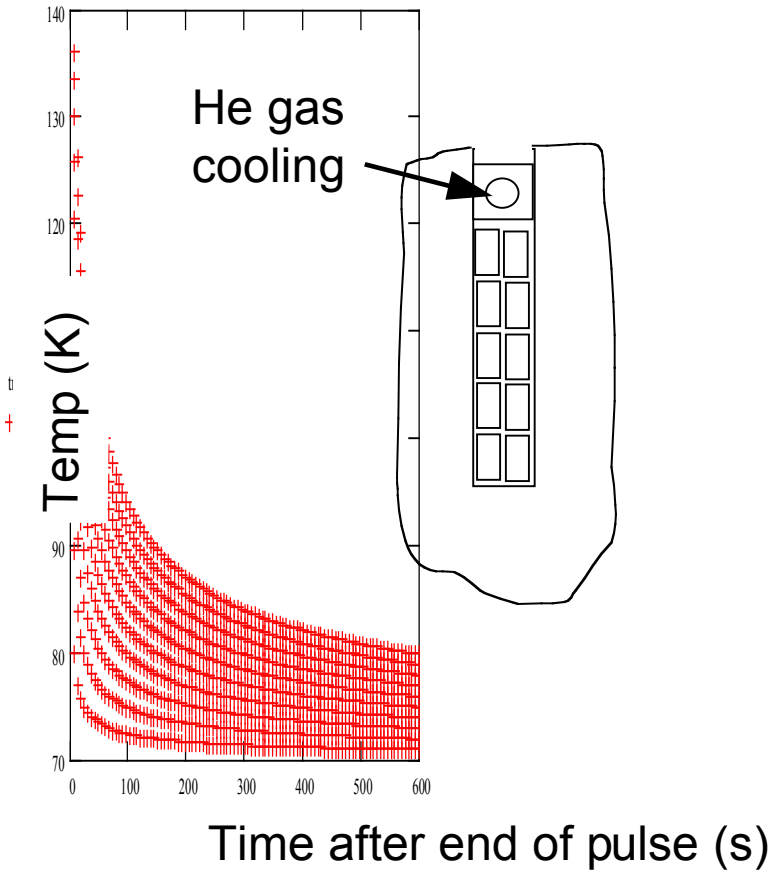


Coil power > 100 MW for typical case



What about cooldown, 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
- Details must be determined by R&D

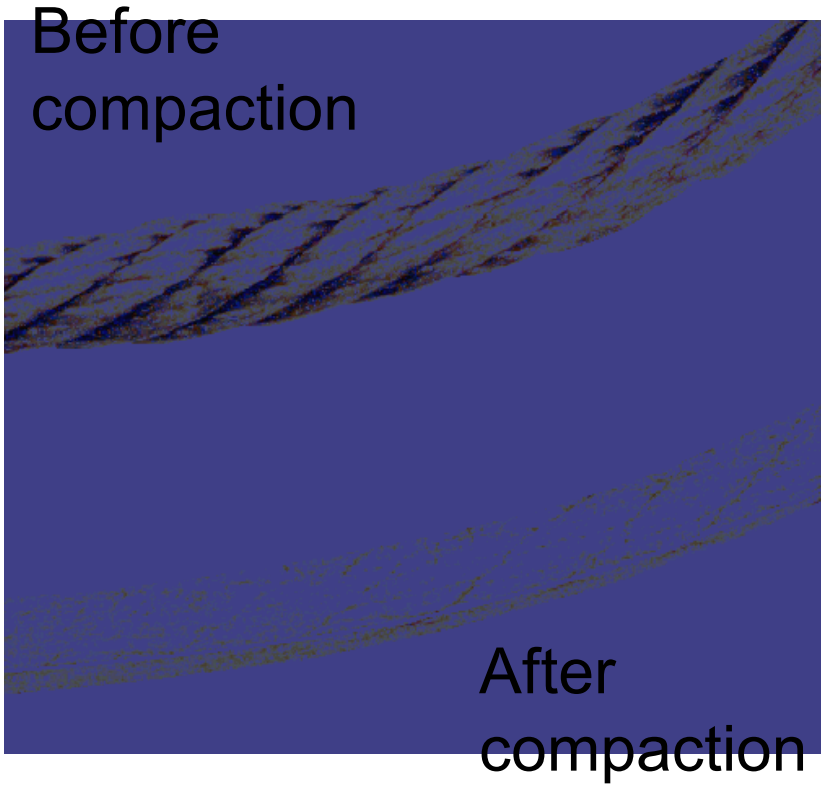


What about fatigue?

- The fatigue life of the cable windings depends on the local strain behavior over multiple shots, both in the copper and the insulation
- average current per strand of conductor, and thus the local force on an individual strand, will be higher for higher current density
- Higher temperature excursions during a pulse will result in higher thermal stress and possible shear stress between the copper and the insulation
- Difficult to quantify the actual fatigue life without testing, so the limits based on fatigue are TBD until coil R&D test results are available.

What about the minimum bend radius?

- The cable conductor is made from very fine (36 Gage) wire
- Even after compaction, this cable is very flexible, and can be readily wound on a radius of 1.5 times the conductor thickness
- Recommend bend radius of 3 times the thickness to avoid excessive key-stoning and bunching



What about the conductor slot width?

- To machine the shell grooves with conventional tooling and machine tools to a depth of 70 mm or more, the groove width must be at least 13 mm wide, and preferably wider (10mm rough, 3mm cleanup)

- The depth of a single machine cut in such a complex geometry is limited to no more than the diameter of the cutter, so even at a width of 13 mm, it would require at least 7 separate machining passes to rough in the groove and probably another 4 to 6 to clean it up

- The time on the machine tool (and cost of machining) is almost directly proportional to the total linear amount of machining

- A 13 mm wide groove costs almost twice as much as a 26 mm wide groove, even though more material is being removed in the latter case.

What about the spacing of conductors? (shell ligament width)

- Width of the ligament depends primarily on the magnetic loads, but prefer no thinner than 5 mm for machining purposes

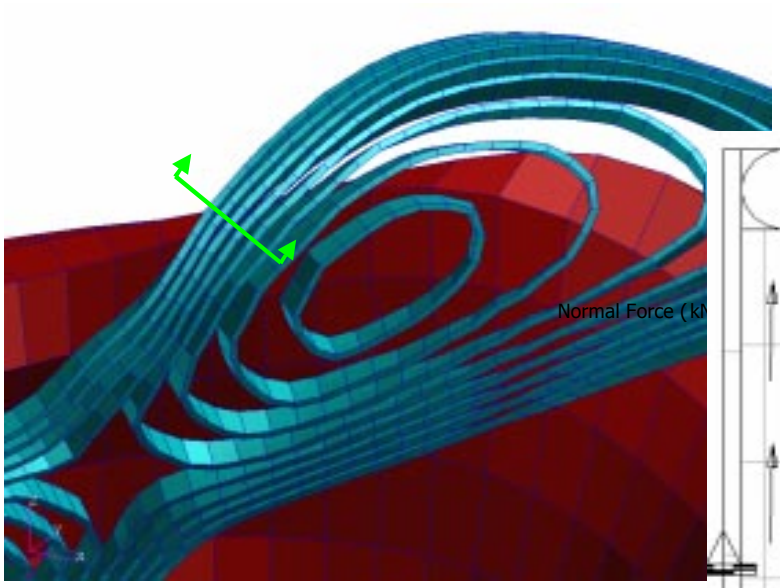
- Stress is linear with load, and the maximum lateral loads appear to vary linearly with the winding current

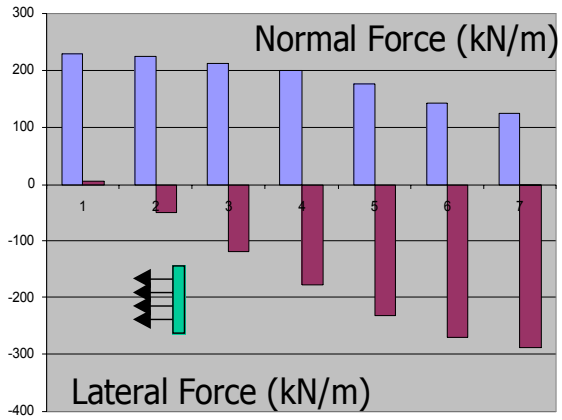
- For a constant stress, the ligament width varies as a quadratic, since the bending stress varies inversely with the square of the thickness and the shear stress varies linearly with the thickness

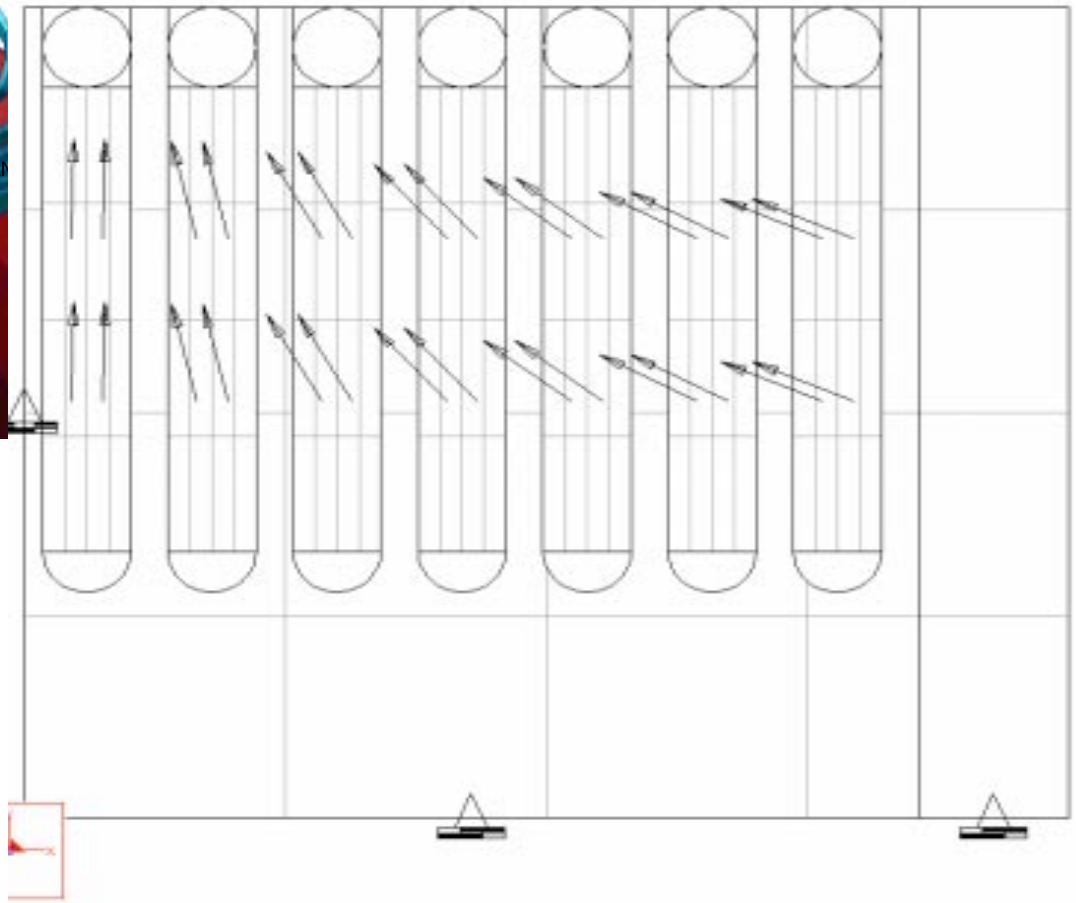
- Most of the stress is bending, so the relationship can be simplified to:

$$W\text{-ligament} = 6 * (I/Inom)^{.5} \quad \text{(but no less than 5 mm)}$$

Magnetic forces tend to bend and shear ligaments

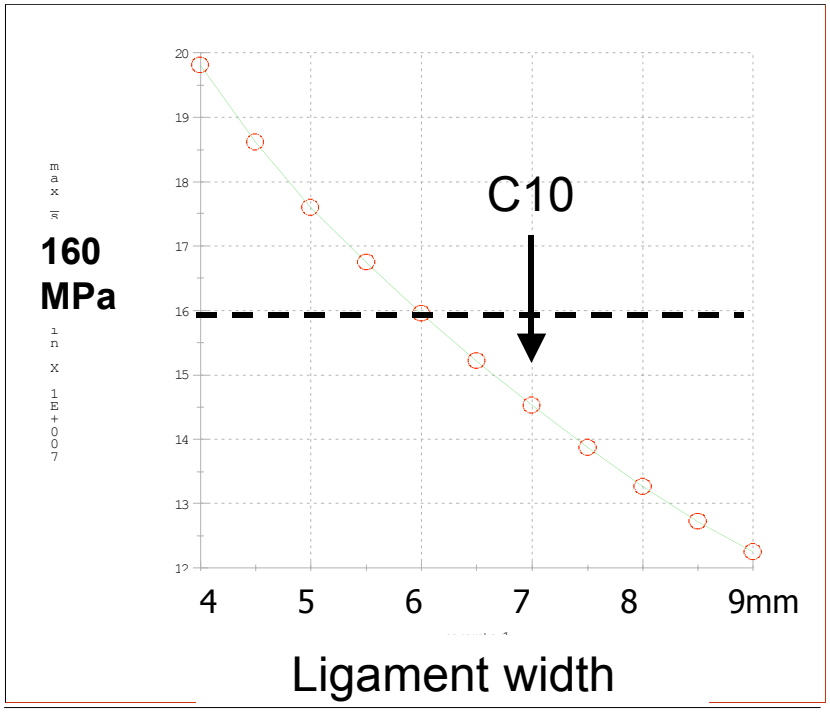


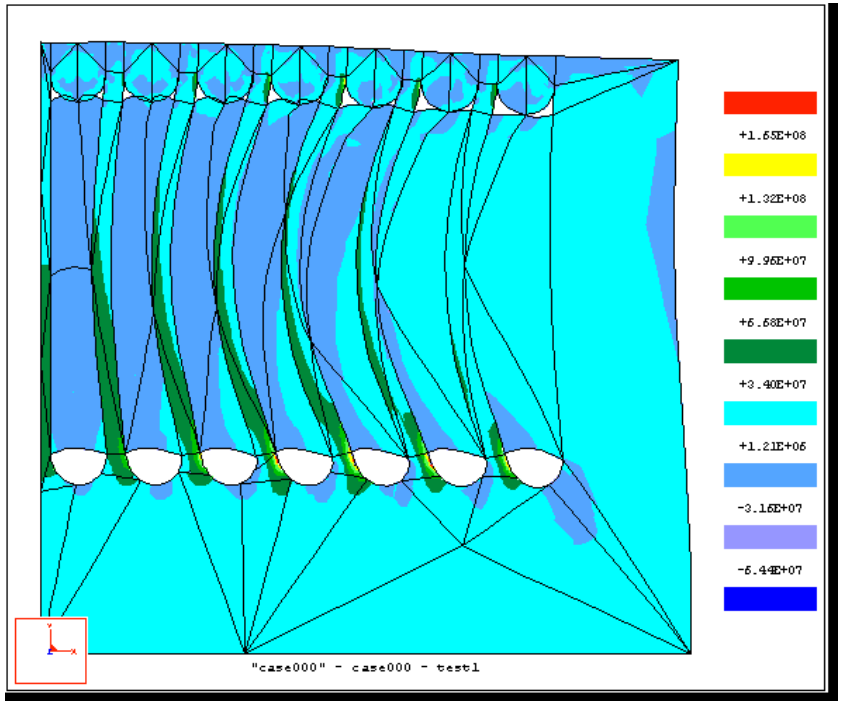




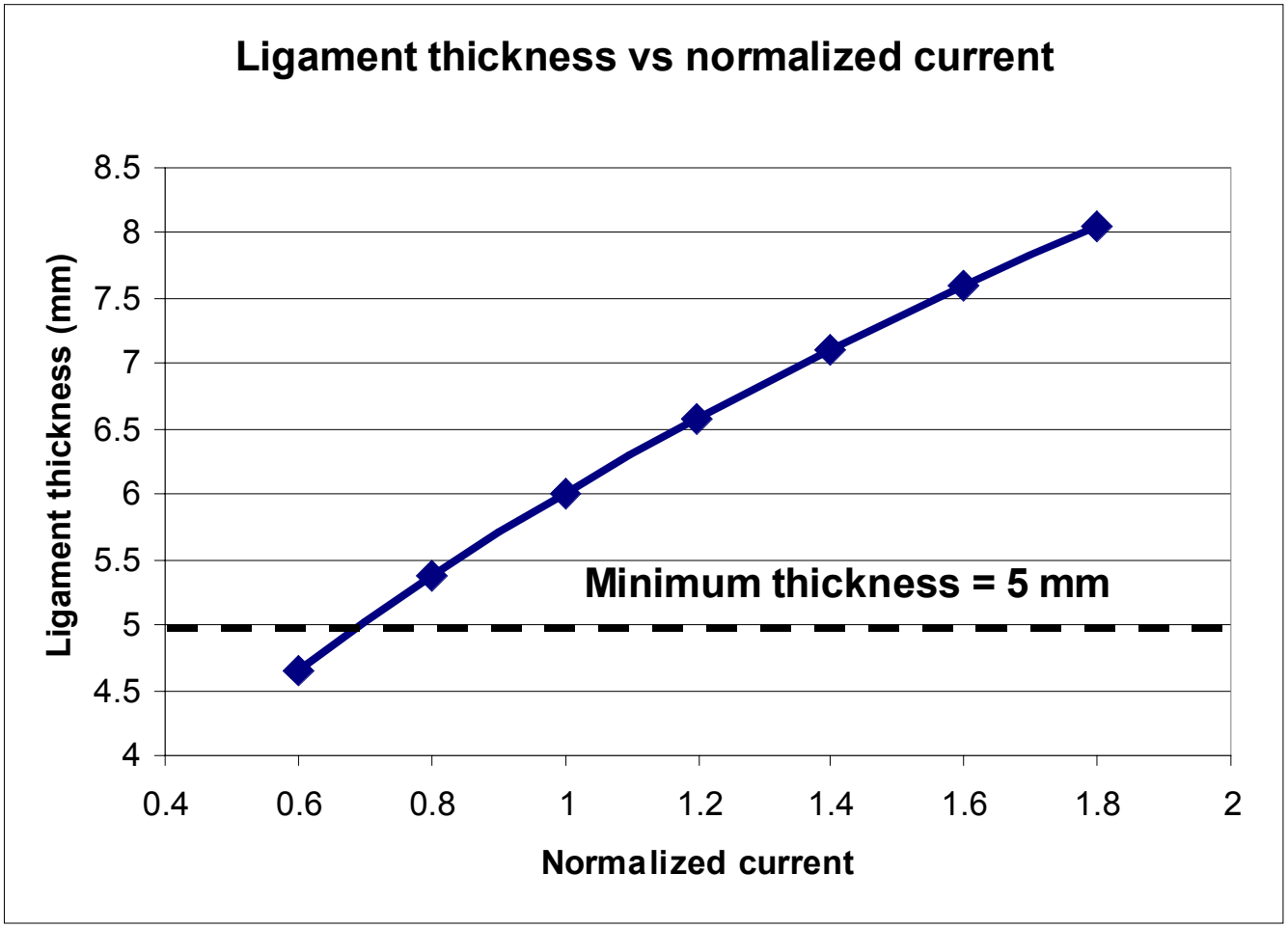
Ligaments between windings must react forces
Minimum ligament for C10 ~6 mm

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





Ligament thickness must be scaled with current



Draft Recommendations - Pending further R&D

Parameter	Limit	Comment
Maximum current density in copper	~22 kA/cm^2	1.03 s ESW pulse Temp <180K, (power limit)
Nominal current density in copper	~18 kA/cm^2	20 % variation in current for flexibility
Nominal gross current density over winding	~7 kA/cm^2	Overall packing fraction, incl. insulation, <40%
Minimum bend radius	3 * Wcond	Limited bunching, keystoning
Minimum shell groove width	13 mm	Based on machining limits
Minimum separation of windings (ligament width)	Greater of 5mm, or 6 * $(I/Inom)^{0.5}$ mm, Inom = 84 kA	Based on stress in ligament

Lower current density and fewer, wider grooves are preferred from cost and performance standpoint

Cable conductor design criteria summary

- Primary issue with cable conductor was stiffness
  - thermal stresses limited temperature
  - temperature limited pulse length

- R&D indicates that stiffness is low, temperature is limited by other factors
  - insulation temp. limits
  - copper, insulation fatigue
  - power 180K max temp is factor of 5 on power
  - cooldown

- Criteria document has been written based on nominal limits, but final document must wait for R&D, including fatigue testing

Plans for saddle coil winding R&D are evolving

Original Plan:

- Cable conductor
  - Fabrication of conductor
  - Stiffness in compression
- Coil fabrication
  - Practice coil winding / potting
  - Develop winding closure system
  - Wind full scale coil in contoured form
- Coil operation
  - Cyclic testing of simple coil at LN2 temperatures

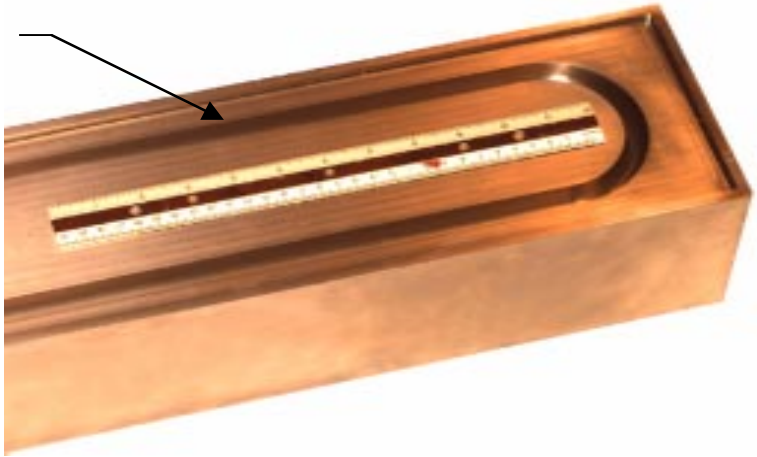
Status:

- Conductor fabricated and tested in compression
- Lexan and Bronze coil forms manufactured
- New, smaller coil form at vendor

Saddle Coil Fabrication

Original Winding/Thermal Cycle Test Fixture

0.5-in wide x .665-in deep + full radius

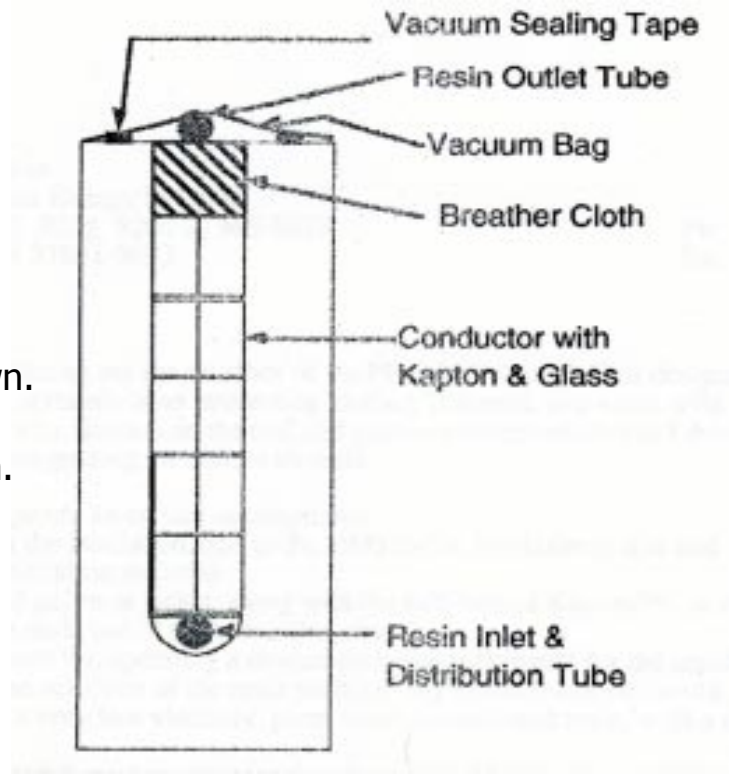


Saddle Coil potting

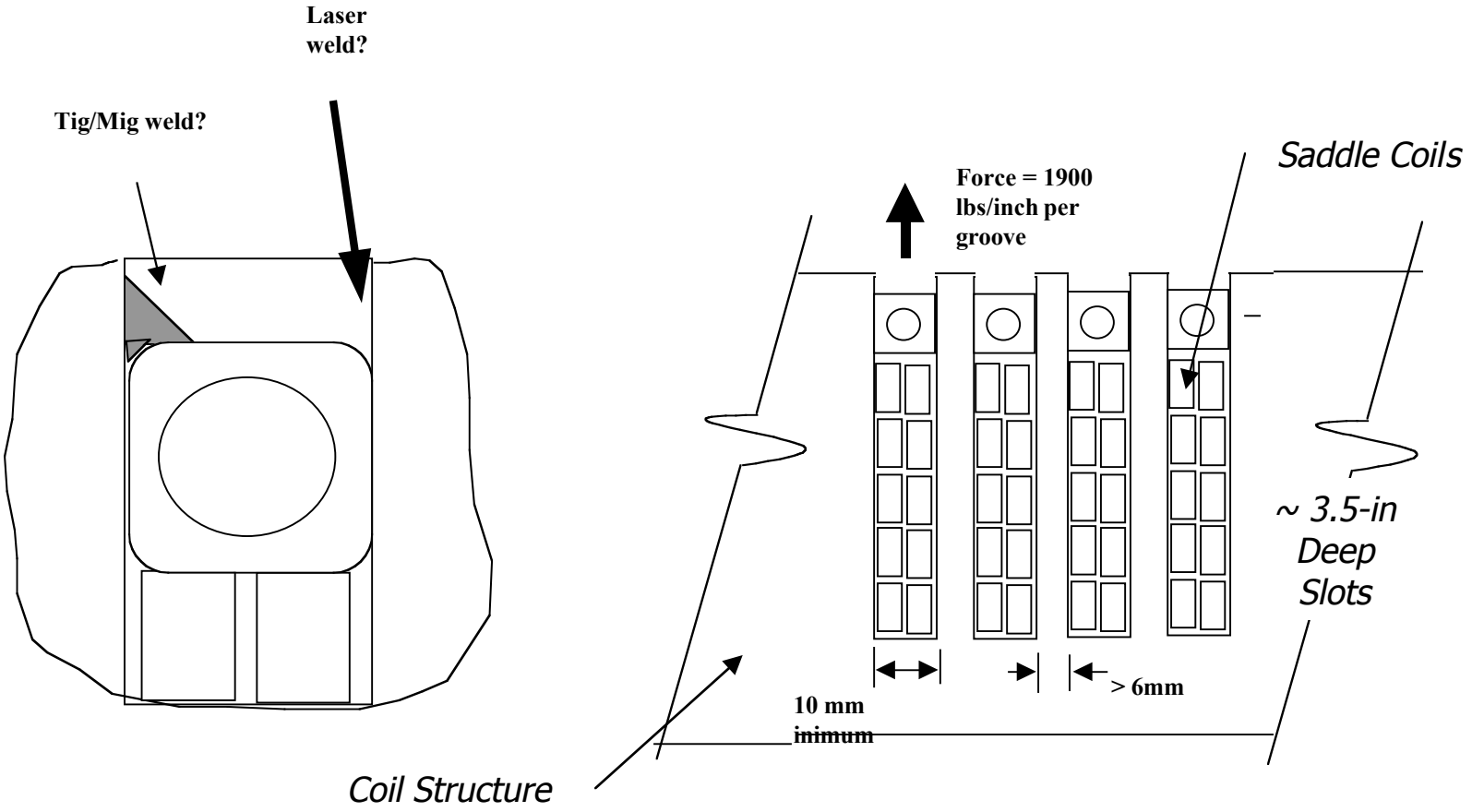
Winding/Thermal Cycle Test Fixture

Potting Tests

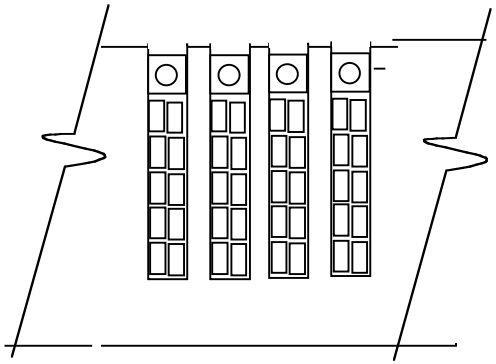
- Potting proposal received from Composite Technology Development, Inc.
- Recommend CTD528, a low viscosity, room temperature cured resin.
- Recommend resin inlet/outlet scheme shown.
- To be tested in thermal cycle test specimen.

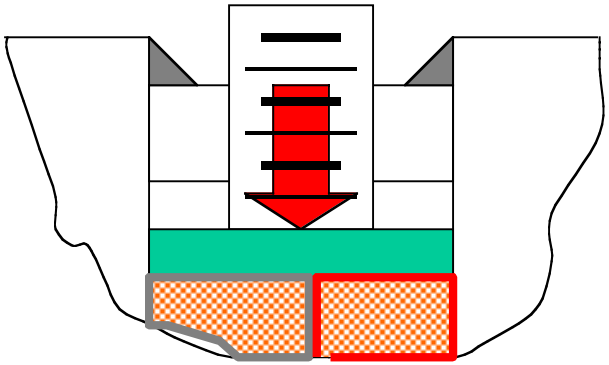


Saddle coil structural closure



What if we preload the winding pack through the structural closure?



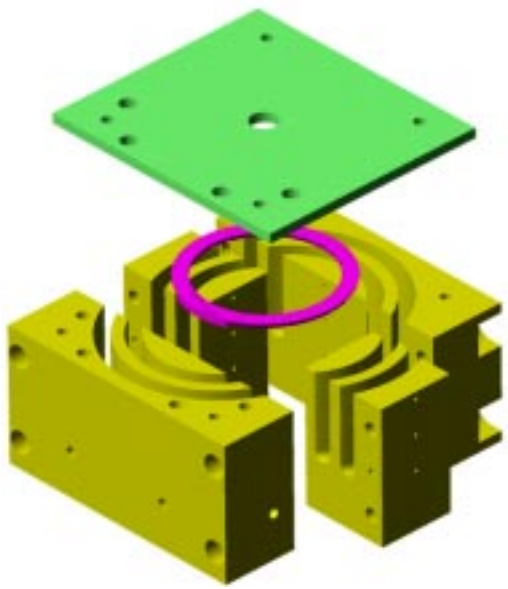


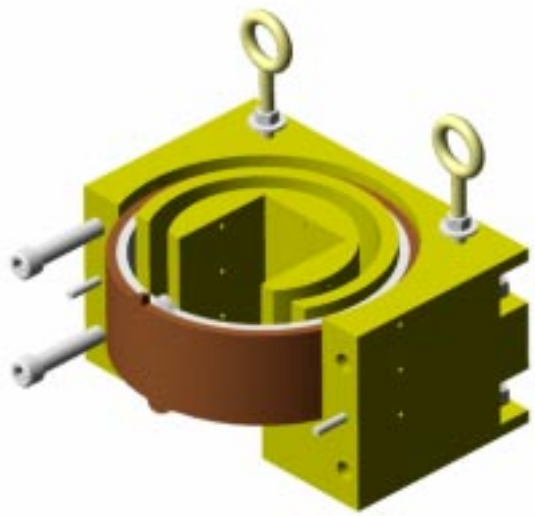
- The winding could be pre-compressed up to the expected magnetic loading to avoid most of the motion during operation

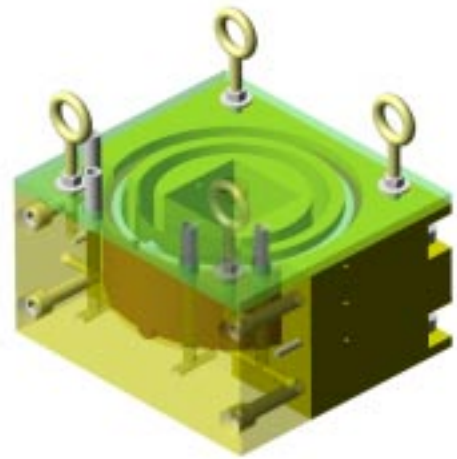
- Potting may be unnecessary
  - fewer voids or gaps to fill after preloading
  - the winding would stay in better contact with the groove walls
  - cooling may be better w/o potting

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

Status
- Drawings complete and at vendor
- Material in hand
- Stereolithography parts ordered



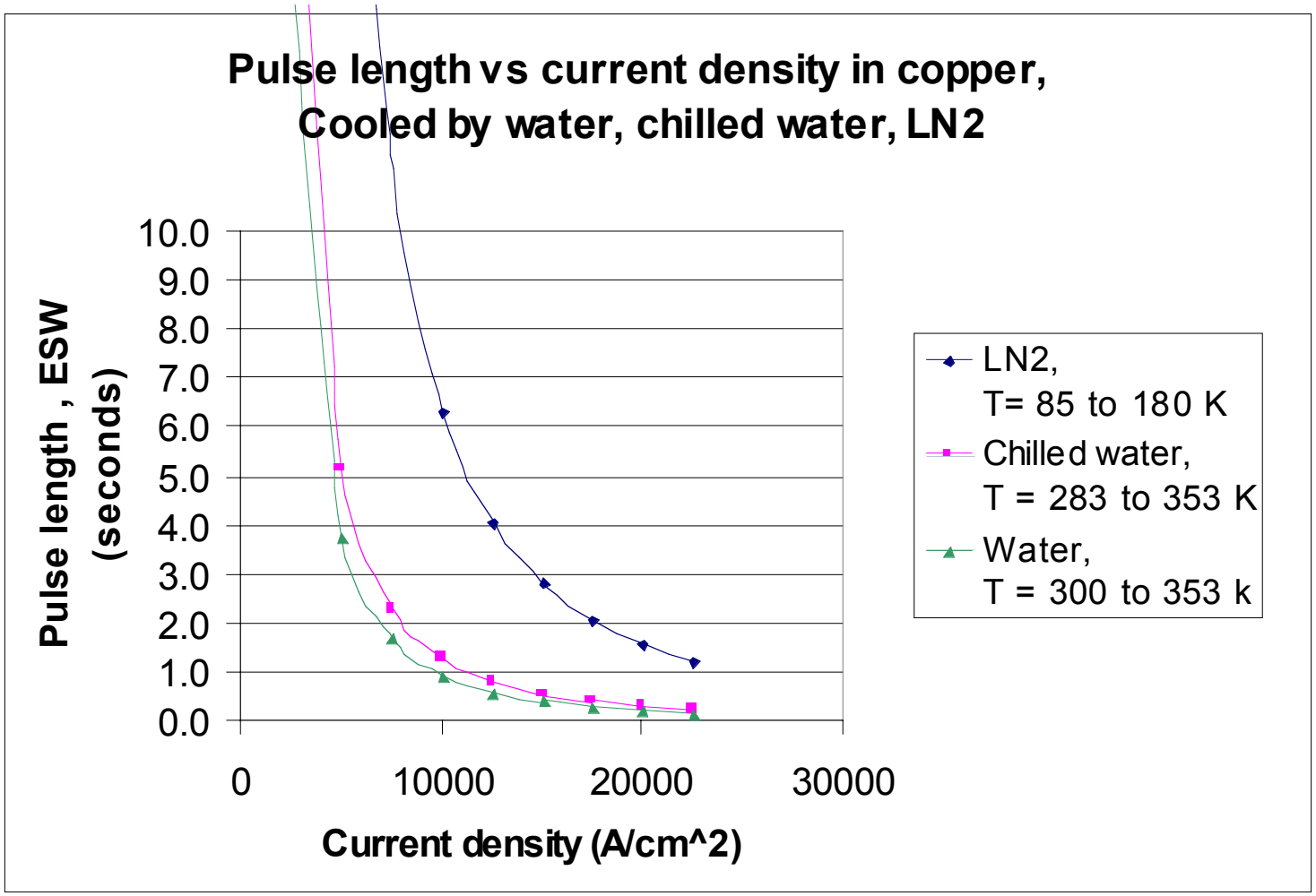




Everything was going ok (a little behind) and then:

- New coil topologies and configurations show remarkable decrease in saddle coil current densities:
  - C82 has current density of ~ 25kA/cm^2 at 2 Tesla
  - New configuration, case 121, reduced to ~9 kA/cm^2
- Water cooling may be feasible in the 10kA/cm^2 range
- So… do we continue with the present R&D plan, or stop to see what happens with the new coil studies?

Water cooling possible at ~ 10kA/cm^2 in Cu



Let’s keep going, but with some mods

- For now:
  - Fabricate the small coil winding form
  - Wind the New England wire insulated square conductor
  - Preload the windings, (do not pot them yet)
  - Perform cyclic thermal and electrical testing
  - Look for loss of preload

- Modify plans as new configuration is developed and key decisions are made

Decision #1: water or LN2 cooling?

- LN2 :
  - continue tests
  - pot the winding, if necessary for cooling and/or structural reasons

- Water:
  - Order new conductor (larger, maybe internal cooling)
  - Remove LN2 compatible winding
  - machine grooves to larger size
  - repeat tests

Decision #2: saddle coils or no saddle coils?

- Keep saddle coils
  - Finish coil testing
  - Continue plans for prototype winding
- Eliminate saddle coils
  - Stop coil R&D until new coil problems identified

Saddle coil R&D status summary

- Some progress has been made in saddle coil R&D
  - Conductor stiffness tests complete (cable is not very stiff)
  - 1000 feet of practice cable in hand
  - New test article designed and in fabrication at vendor

- Saddle coil R&D is being re-scoped to consider water cooled design
  - Larger conductor
  - Different cooling scheme? (eg, internal cooling?)

- Cable conductor cooling, fatigue are main issues to be investigated near term with small coil test