NCSX

WBS 1 Torus systems

- **Issue summary**
- **C82 implications**
- **Plan**
- **Conclusion**

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NCSX Project Meeting
PPPL
March 31, 1999

What are primary open decisions for vacuum vessel?

Issue	Options	Comments	Risk	Resolution
Material	316L stainless	Current baseline, Permeability could be issue	*Medium* (may not meet permeability requirement)	Sharpen magnetic permeability requirement, **Check cost**
	Inconel 625	Stronger, thinner, more costly	*Low* (cost is main issue)	
Fabrication process	Break bending	Current baseline like WVII-AS	*Medium* (software must be developed)	Break bending chosen for baseline
	Explosive forming	like HSX	*High* (hard to predict tooling cost, schedule)	
	Casting, other process	like ??	*High* (vacuum quality casting tbd)	
Assembly	Procured and installed in one piece	Current baseline, best procurement option	*Low* (vessel ok before shipping)	3 piece vessel chosen to accommodate shell assembly
	3 pieces joined from inside	Offers more flexibility for shell assembly	*Medium* (vessel not leak-checked prior to final assembly)	
Cooling / Heating fluid	Water / Steam	Should be cheaper, if corrosion not an issue	N/A	Resolution based on cost only
	Dowtherm	Used for NSTX	N/A	

What are primary open decisions for saddle coil windings?

Issue	Options	Comments	Risk	Resolution
Conductor current density is too high due to close spacing of coils 3-D effects make grooves even tighter at root of bends	Reduce temperature of coil to increase pulse length	Expensive to sub-cool LN	*Low* (cost is main issue)	Check cost
	Reduce number of turns to increase packing fraction	Increases field errors, Conductor is harder to wind	*Med* (design of leads is more difficult, may not have winding solution)	Must be resolved by physics
	Fewer coils	Poor reconstruction	*High* (may not have workable coil set)	Must be resolved by physics
	Put coils closer to plasma	Can't go much closer than 18 cm	*High* (shell design, vv tolerances, therm insul. More difficult)	18 cm retained as minimum gap for baseline design
	Put two saddles in one groove in tight regions	May have second order benefit, but cooling, winding accuracy may suffer	*Med* (machining details of groove may be tricky)	Must be resolved by physics
Cooling of conductor	Conduction to shell	Better use of space, depends on material of shell	*Low* (most straightforward concept)	Conduction to shell chosen as baseline
	Conduction to strap	Works for any material	*Med* (strap cooling not easy)	

Issue: Current Density and Pulse Length

- Coil geometry pushes design to higher current density

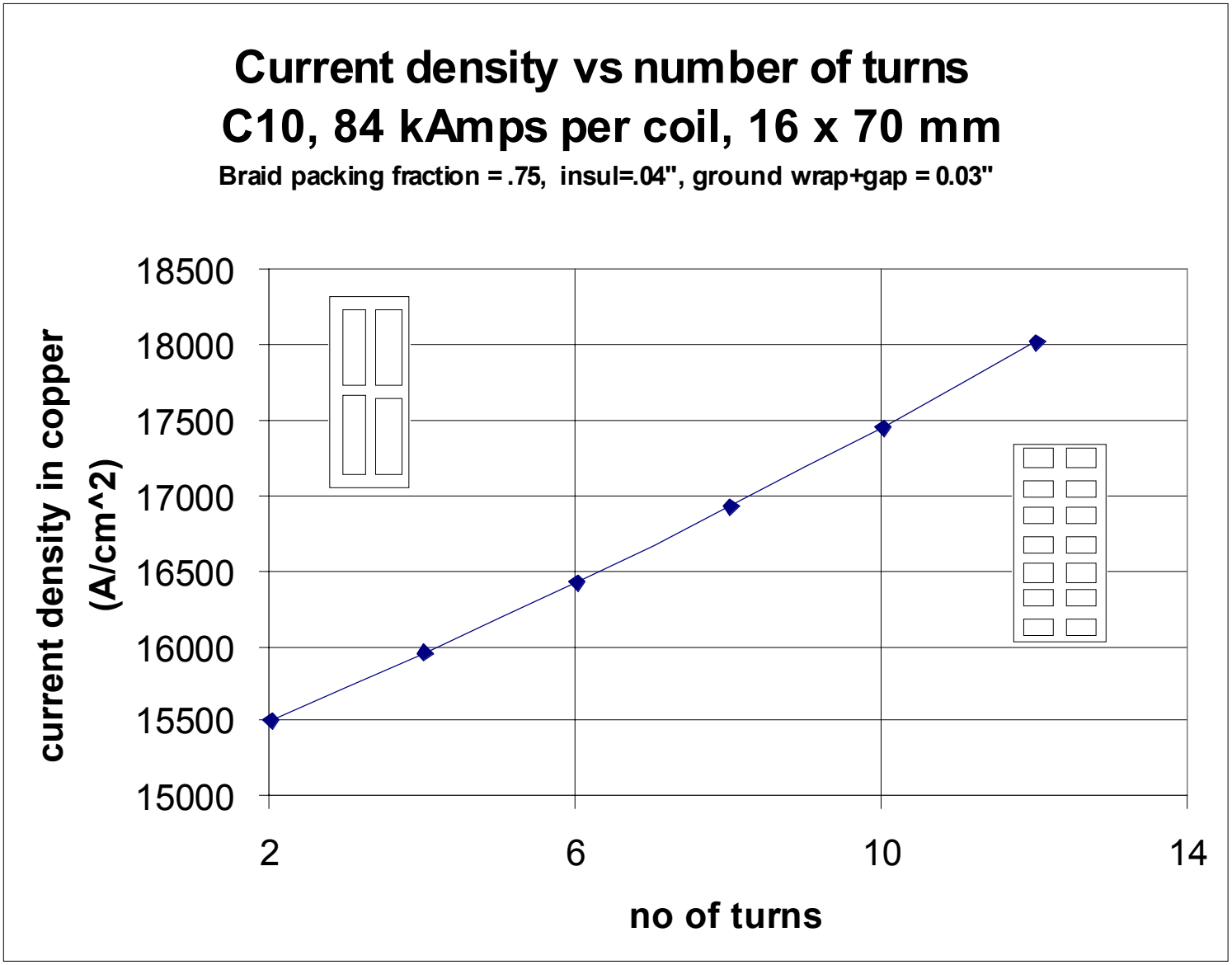
  - -Winding centers can be closer to plasma surface
  - Adjacent windings can be closer to each other

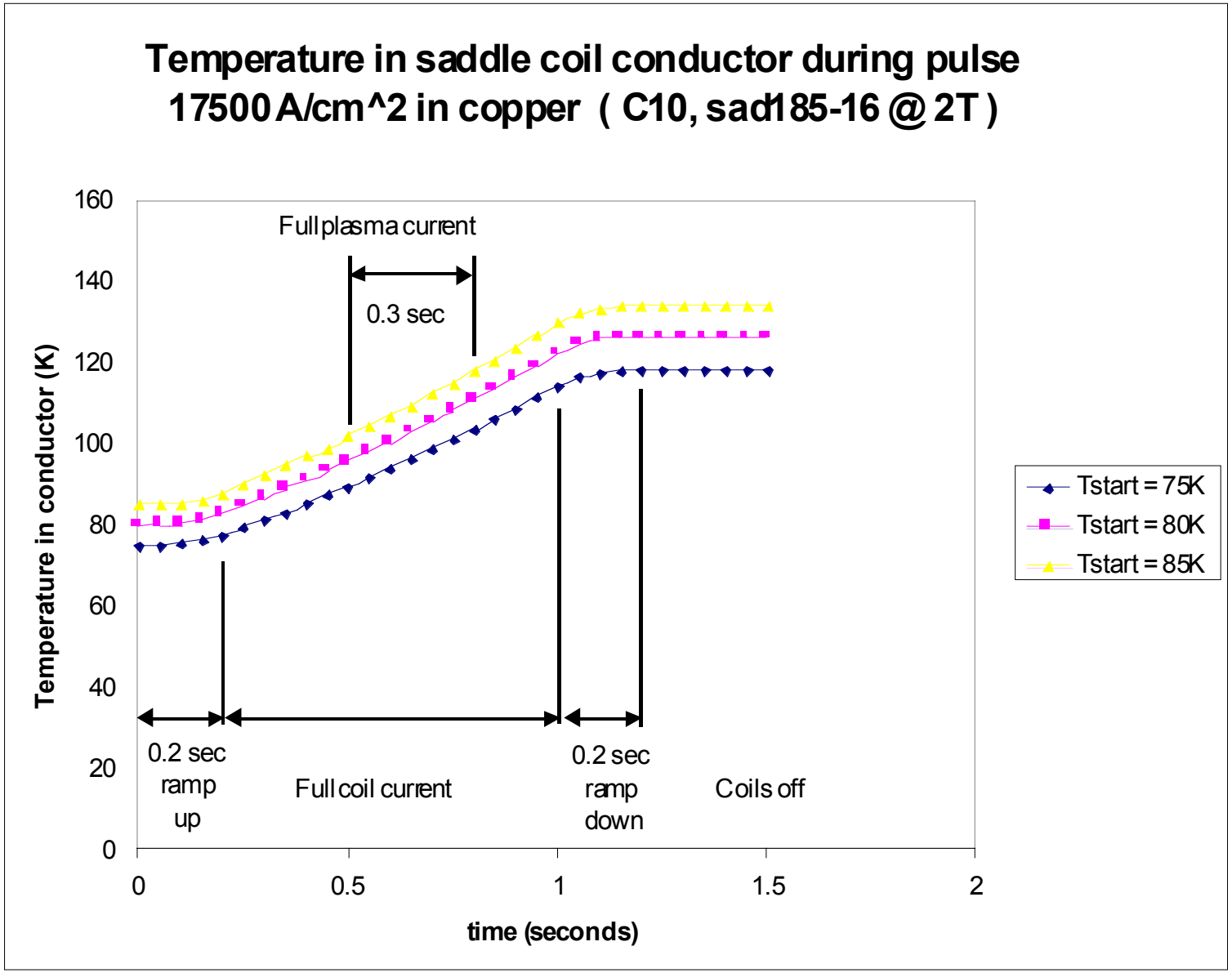
- Current density determines pulse length for adiabatic heating

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

- Baseline design (C10)

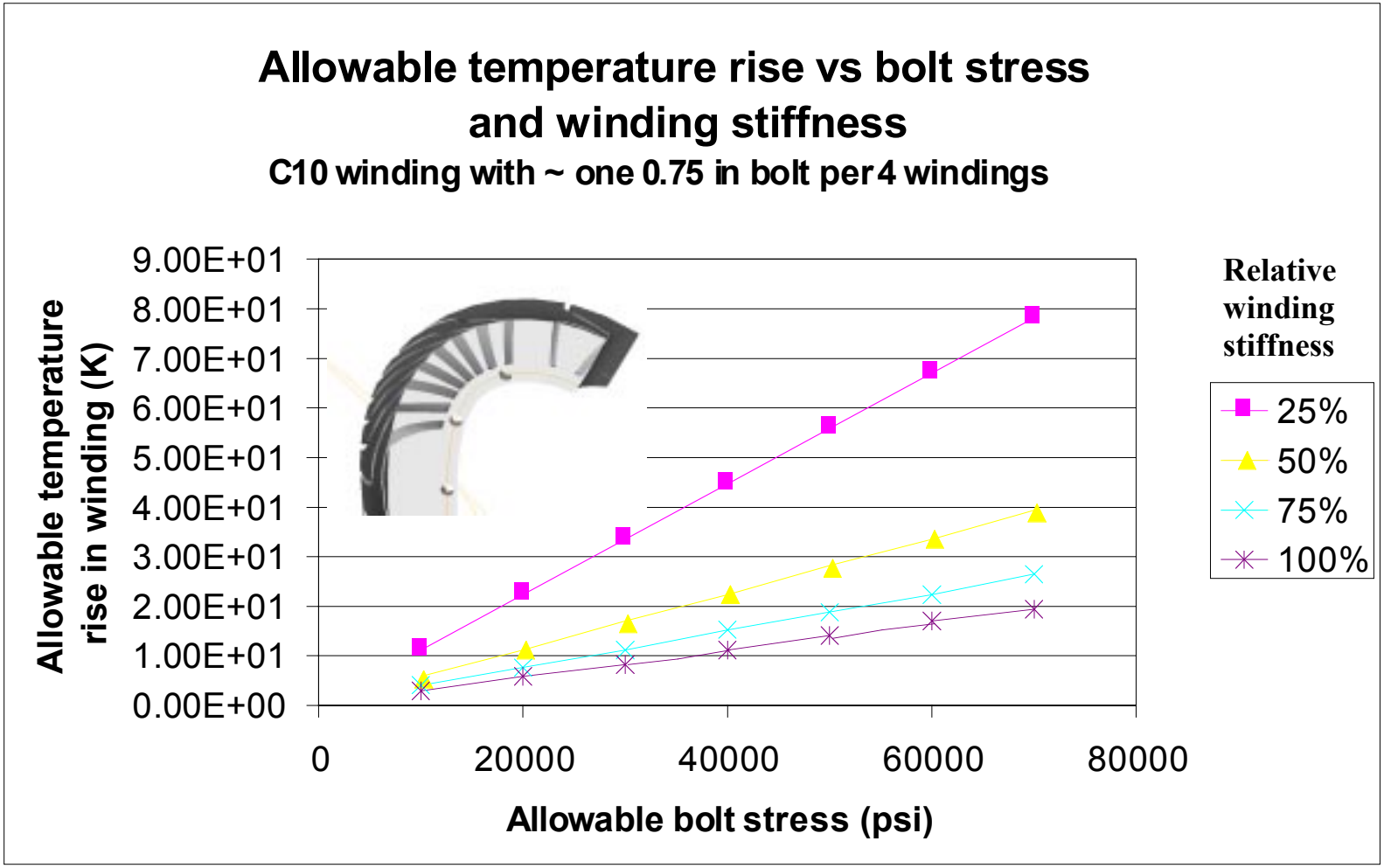
  - Number of turns per saddle coil = 10
  - Current density in copper **~17.5 kA/cm^2 at 2 T**
  - Pulse length for 80 to 130 K rise = ~**1 second** (equivalent square wave)
  - Power at end of pulse ~45 MW


Current density vs number of turns
C10, 84 kAmps per coil, 16 x 70 mm
Braid packing fraction = .75, insul=.04", ground wrap+gap = 0.03"
current density in copper (A/cm^2)
18500
18000
17500
17000
16500
16000
15500
15000
2
6
10
14
no of turns

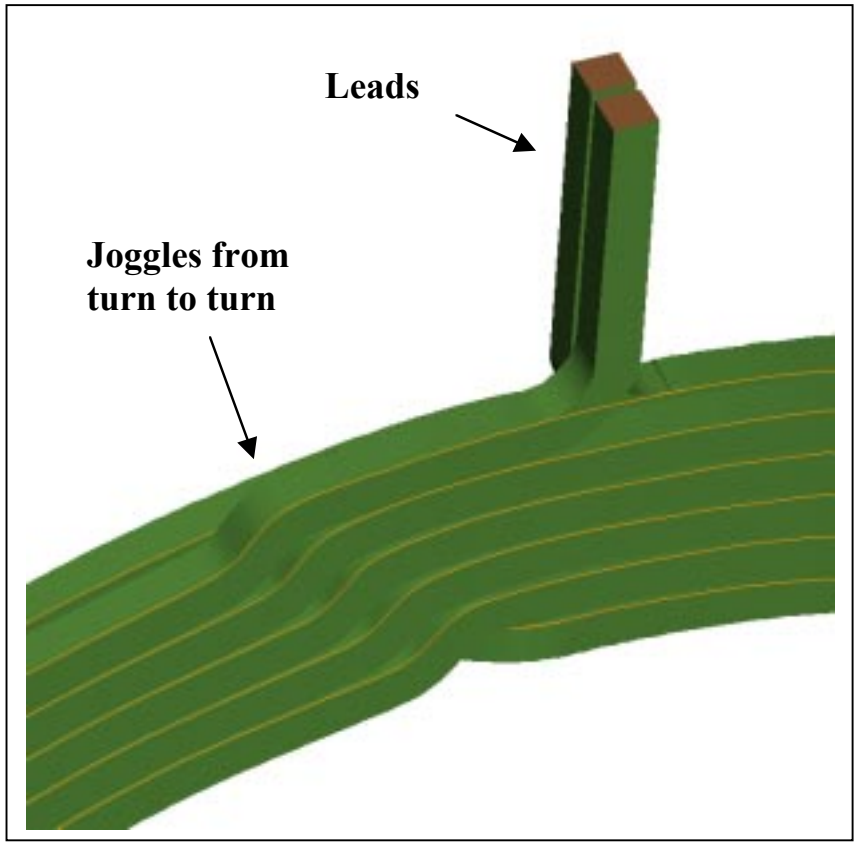

Temperature in saddle coil conductor during pulse
17500 A/cm^2 in copper (C10, sad185-16 @ 2T)
Temperature in conductor (K)
time (seconds)
Full plasma current
0.3 sec
0.2 sec ramp up
Full coil current
0.2 sec ramp down
Coils off
Tstart = 75K
Tstart = 80K
Tstart = 85K
0
20
40
60
80
100
120
140
160
0
0.5
1
1.5
2

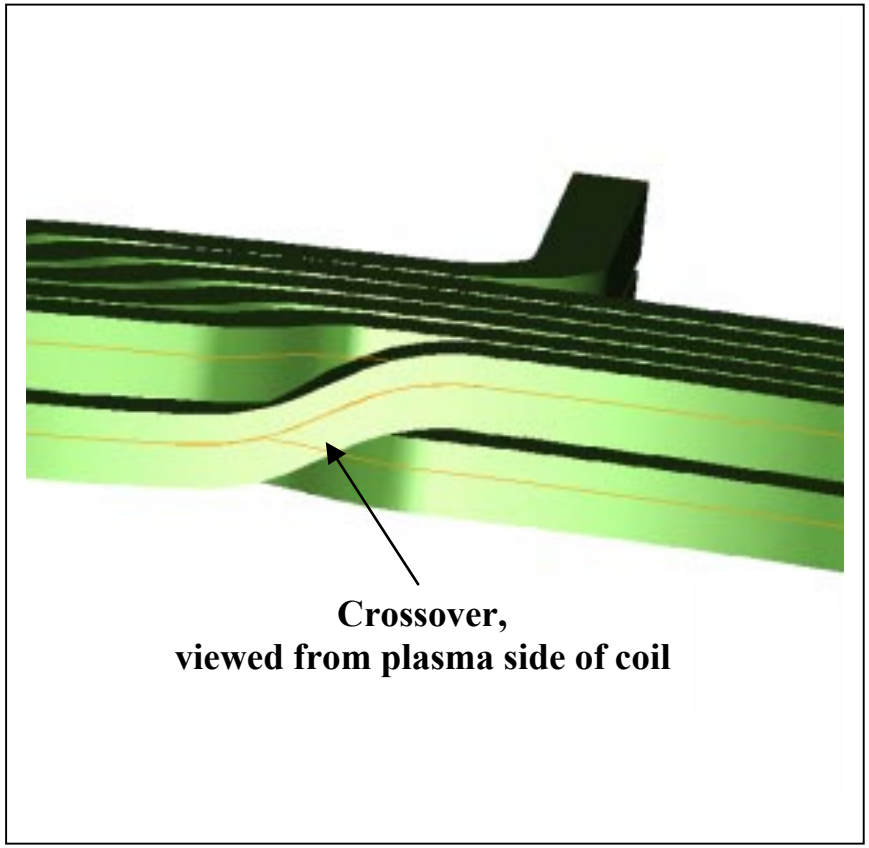
Thermal stress in conductor limits temperature rise

Temperature rise in winding will stress shell bolts depending on winding stiffness

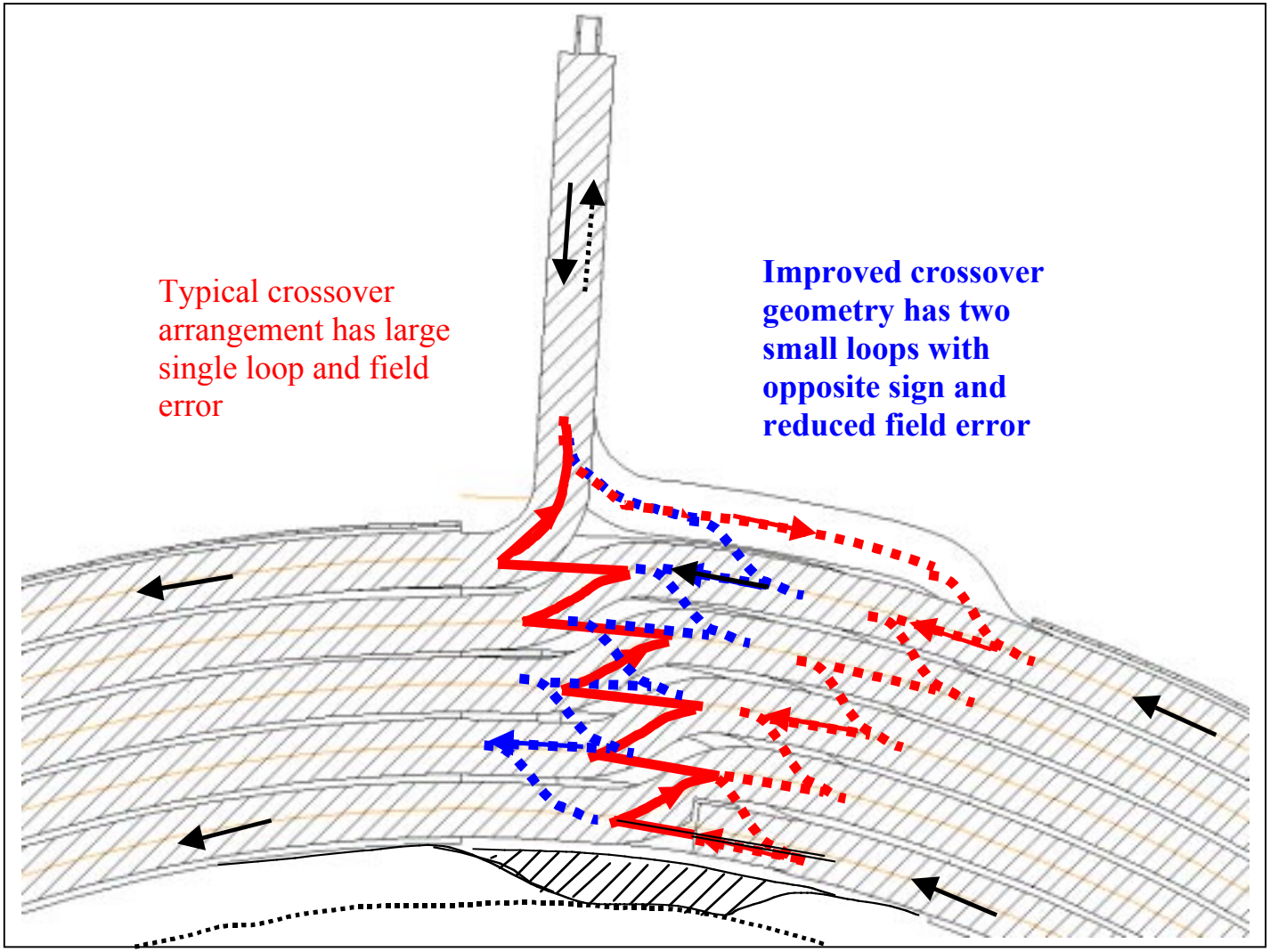


Crossovers and joggles require attention





Field error can be reduced by shifting crossover



What are primary open decisions for structural shell?

Issue	Options	Comments	Risk	Resolution
Fabrication option	Wedges	Material Fastening wedges together	*Med* (wedge joining main issue)	8 wedges per field period chosen as baseline
	Ribs with epoxy fill	Material properties, fastening ribs together, behavior of composite structure at LN temperature	*High* (Fill operation is high risk)	
	Structural shell with epoxy fill	Material properties, cost of two nested shells	*High* (same as above)	
Shell material	304L stainless	Good except for machining and thermal conductivity	*Low*	Shops prefer aluminum or bronze, but time constant eliminates aluminum Bronze alloy C95800 chosen for baseline concept
	Bronze alloy	Good, but hard to weld, may have permeability problem (μ = 1.05 to 1.15)	*Med*	
	G-10	Low electrical conductivity, hard to machine, bad CTE	*High*	
	Graphite epoxy	Not clear	*High*	
Cooling	Closed loop	Safer, more complicated	*Med* (leaks)	Total cost for safe system
	Open loop	Like Alcator C-Mod	*Low* (leaks no problem)	

Issue: Shell fabrication feasibility depends on design details

- Casting of forms and accuracy +/-*.25 inch contour tolerance should be no problem, but this will be a sand casting*
- Part configuration *Prefer flats on ends, normal to one side of wedge*
- Pre-machining and/or finish machining *Pre-machining helpful, finish machining of assembly is required*
- Joining bolts *Should cast pocket relief into part, use back spot-facer for bolt head*
- Groove accuracy +/-*.005 inches within one piece can be done, total assembly will be more*
- Groove shape (width, depth, bottom shape) *must be at least 0.5 in wide, full radius at bottom preferred, depth pushing limit at 3.5 inches*
- Surface Finish - *63 rms, prefer to use "cobb" cutter*

Issue: Shell cost and schedule

Cost Issues

Raw material *~$1 to $4 per pound*
Casting patterns *$10k to $20k each*
NC tapes *~200 hours each*
Machining cost: *function of material removal rate and*
Length of groove (not width)
Number of passes (~ depth / width)
$ = c length * depth / width*

⇒ fab $ for 32 coils per period = 4 x $ for 16 coils

Schedule

Machine tool availability *prefer high speed machine*
Number of different parts and setups *fewer parts are better*

Issue: Core weighs more than crane capacity

30 ton crane, 3 ton winding + 43 ton shell + 5 ton vessel = >50 ton assembly

Option 1 Assemble core in PLT test cell

Requires crane upgrade or re-rating of existing crane
Should result in shortest schedule
No lay-down space for PBX components

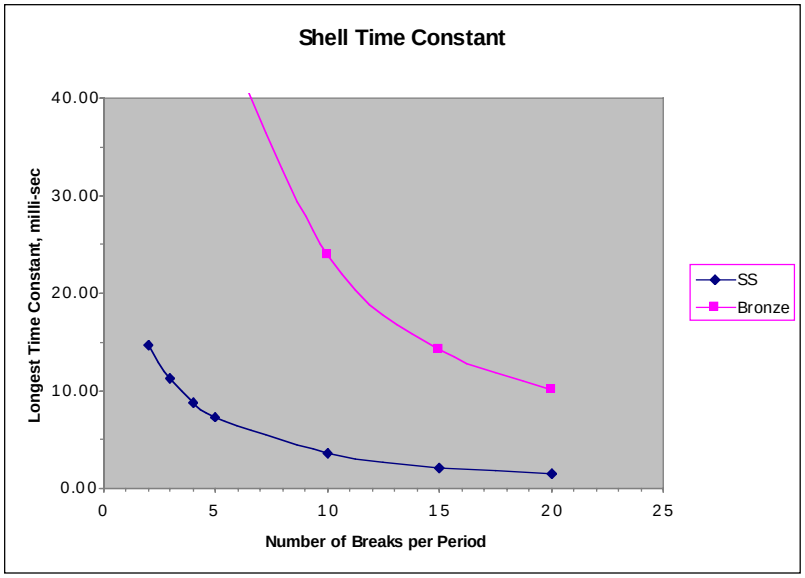
Option 2 Assemble Core in PBX test cell and wind in place

Most parts built in parallel outside
Winding schedule only about 1 year
PLT area provides temporary lay-down space for PBX components

Shell time constant dictates material and number of parts

- Baseline requirement is 10 milli-seconds
- Implications for shell design
  Aluminum not allowed
  Bronze shell must be broken into ~ 120 pieces
- Implications for shell design if limit is relaxed

  Larger contoured castings may be used, which eliminates pieces and saves cost



Ref Art Brooks, 3 May 99

- Calculation of field error as a function of time constant or segmentation would be useful to design process

Issue: C82 vs C10 implications

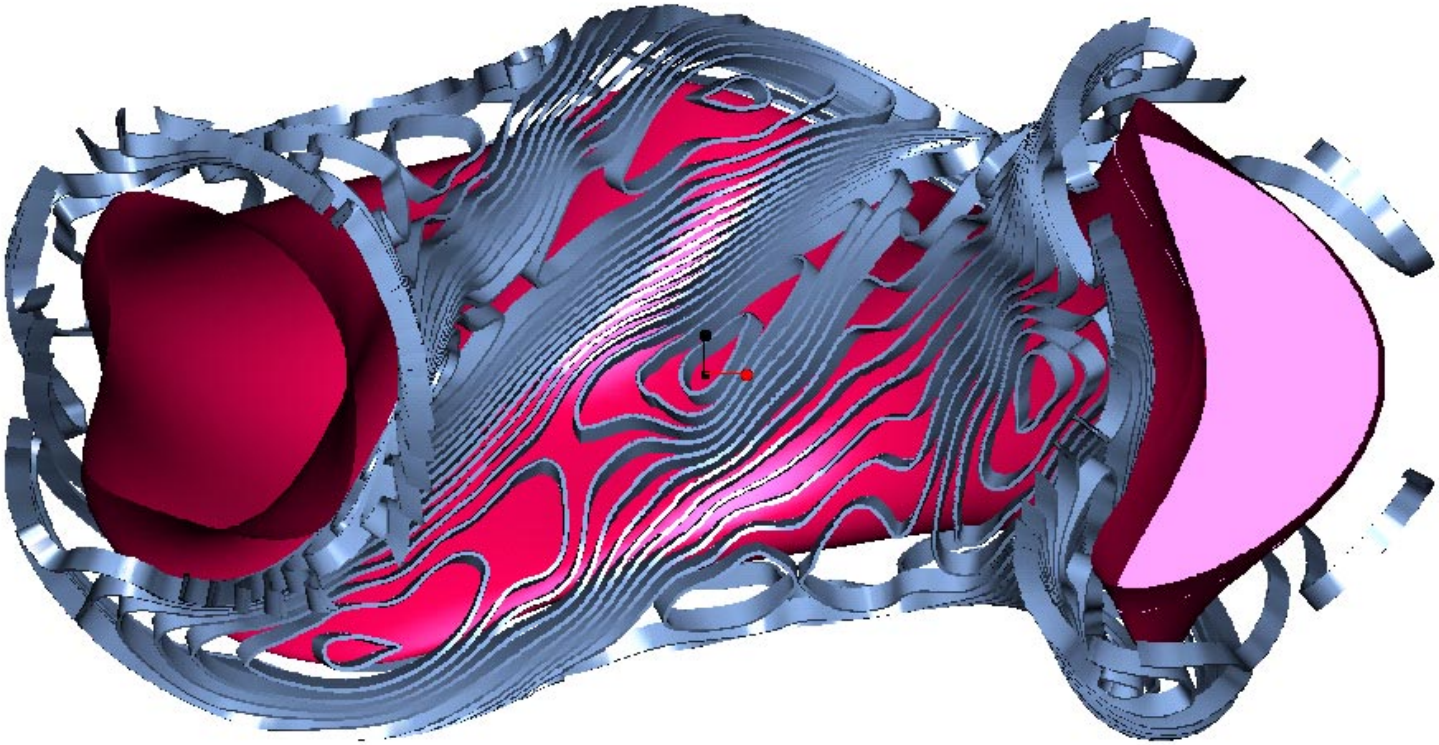
Parameter	**C10, SAD18.5_16**	**C82 FD121_16**
Coils per period	26	26
Current for 2 Tesla at 1.42 m radius	84 kA	91 kA
Plasma to coil center separation	18.5cm IB, 20.5 cm OB	18 cm
Winding dimensions	16 x 70 mm	13 x 70 mm
Net current density	17500 A/cm^2	24600 A/cm^2
Pulse length	> 1 sec ESW	< 1 sec ESW
Winding length	408 m x 10 turns	402 m x 10 turns
Winding separation, center to center	23 mm	> 19 mm, variable
Winding separation, finite coil pack	< 6mm	> 6 mm at corner
Minimum bend radius	8 mm	30 mm

C82 (fd121_16) coils are similar to C10 (sad18.5_16)

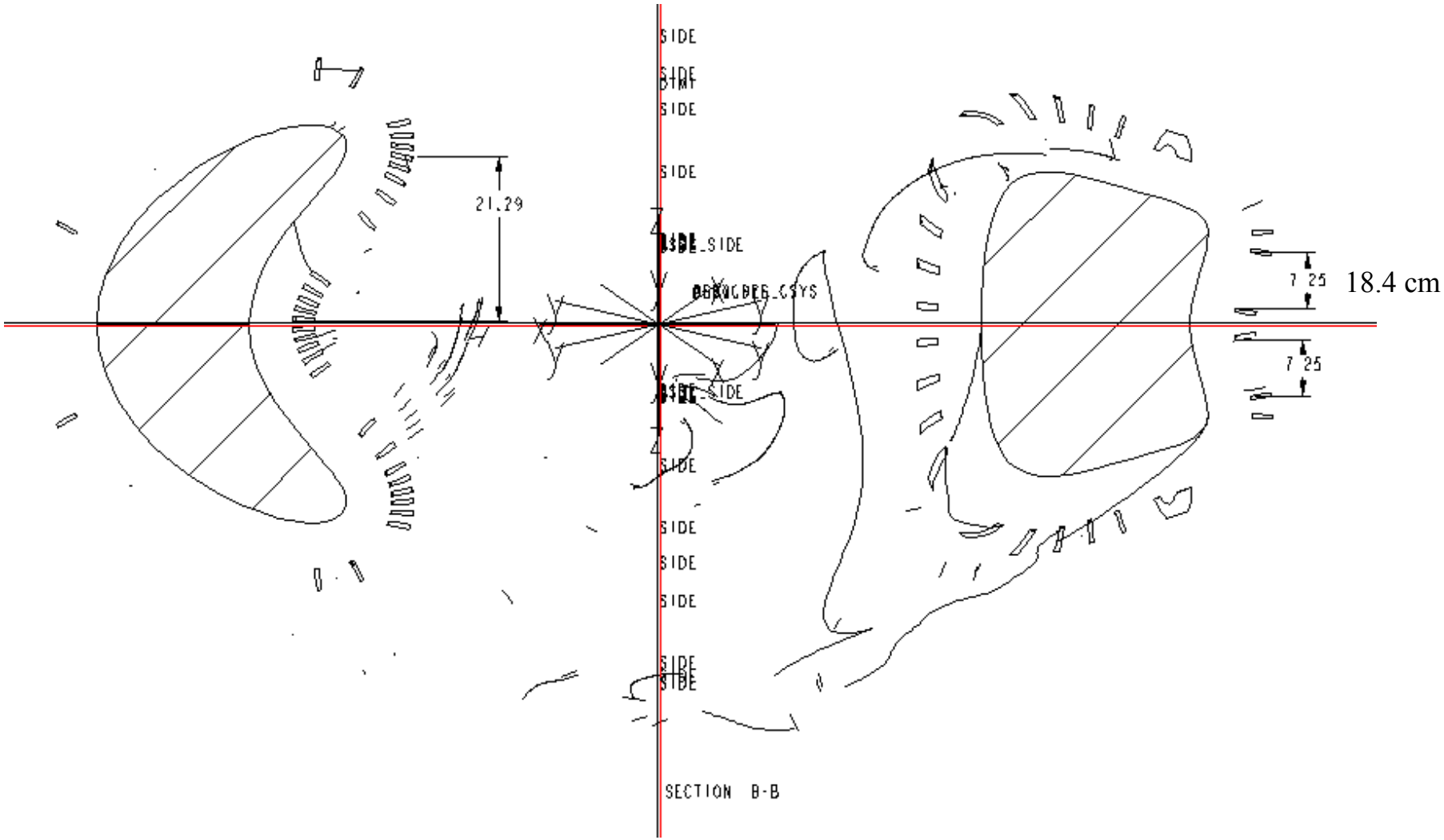
C10

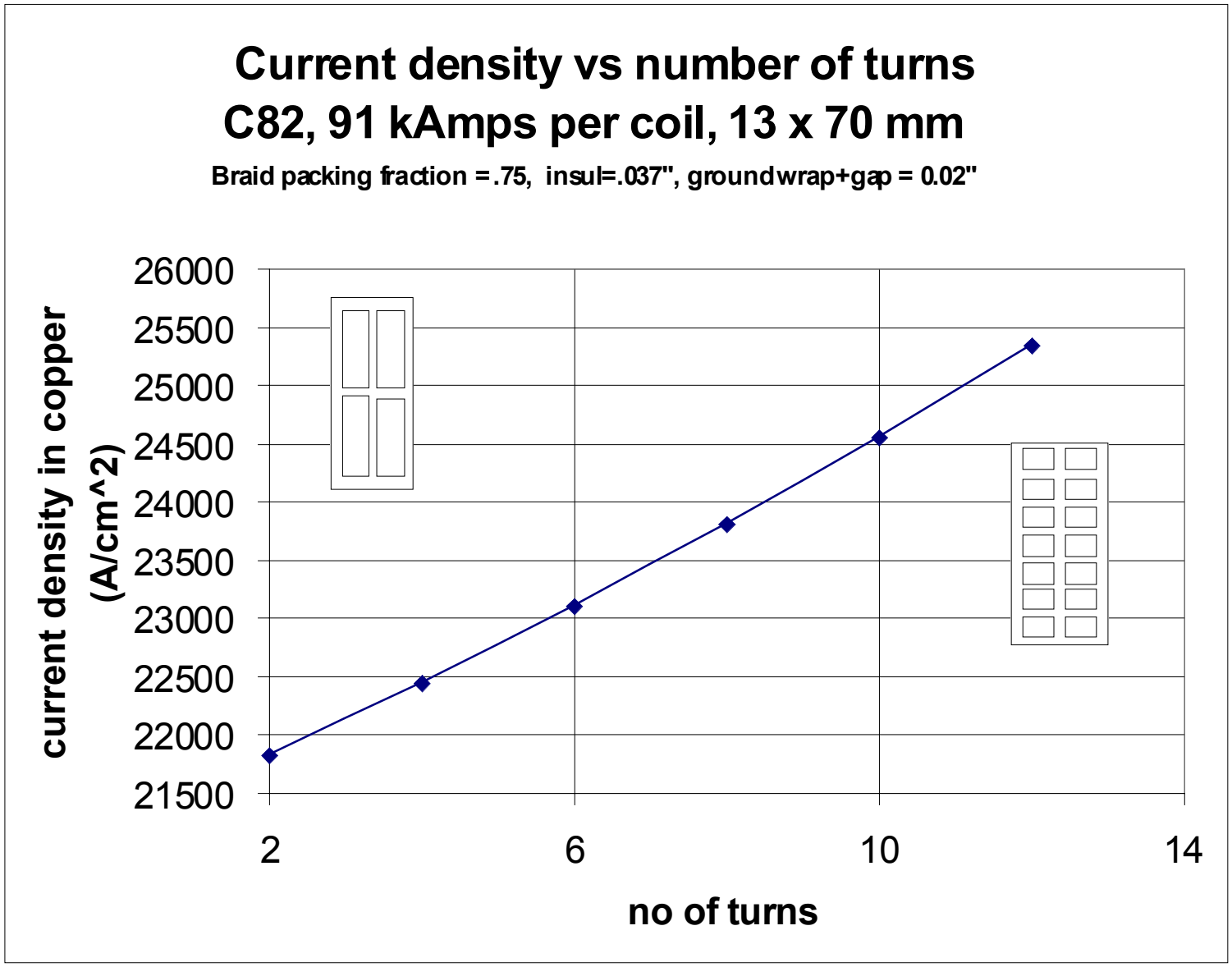
C82

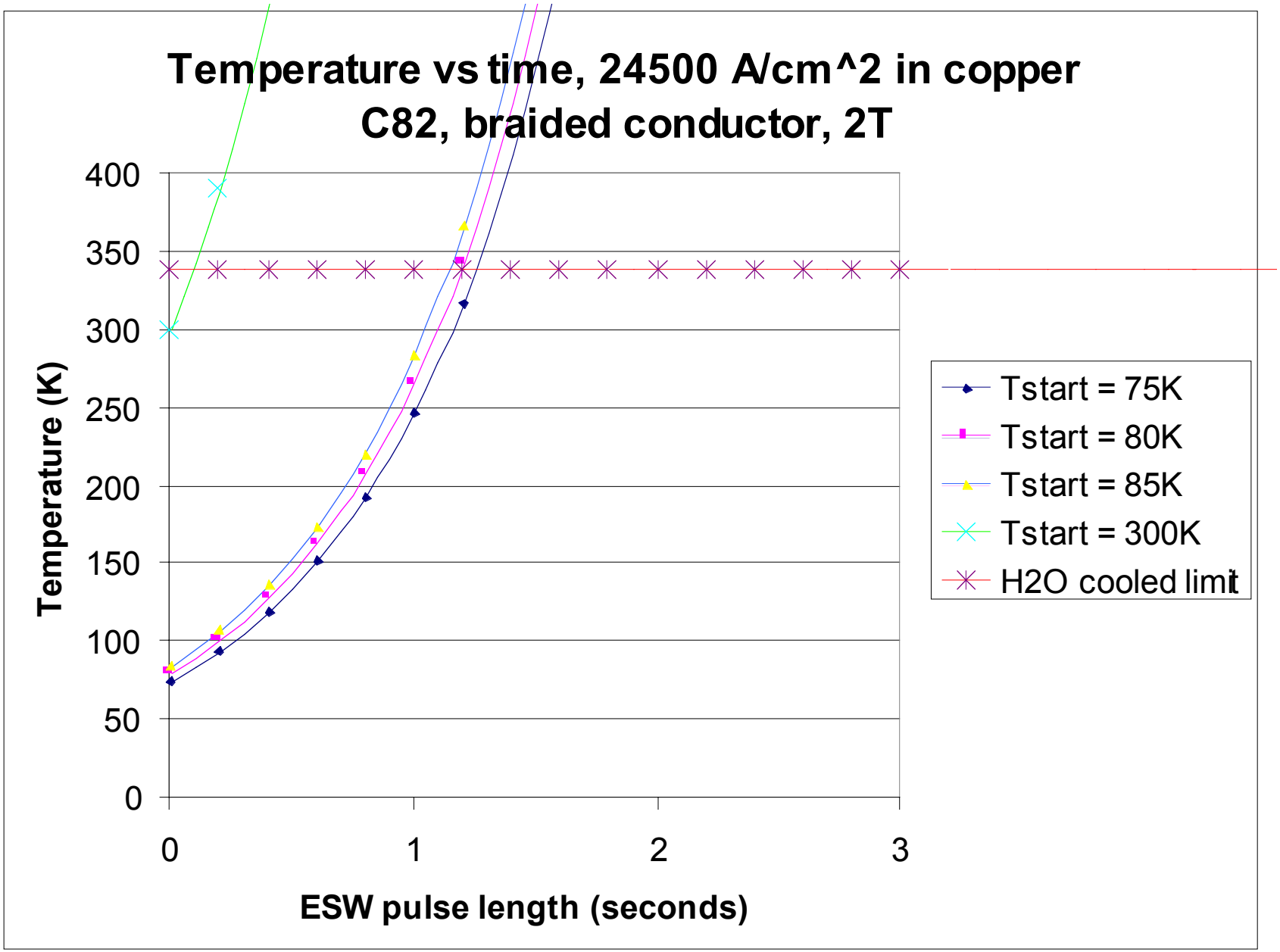
C82 (fd121_16) coils cover inboard region



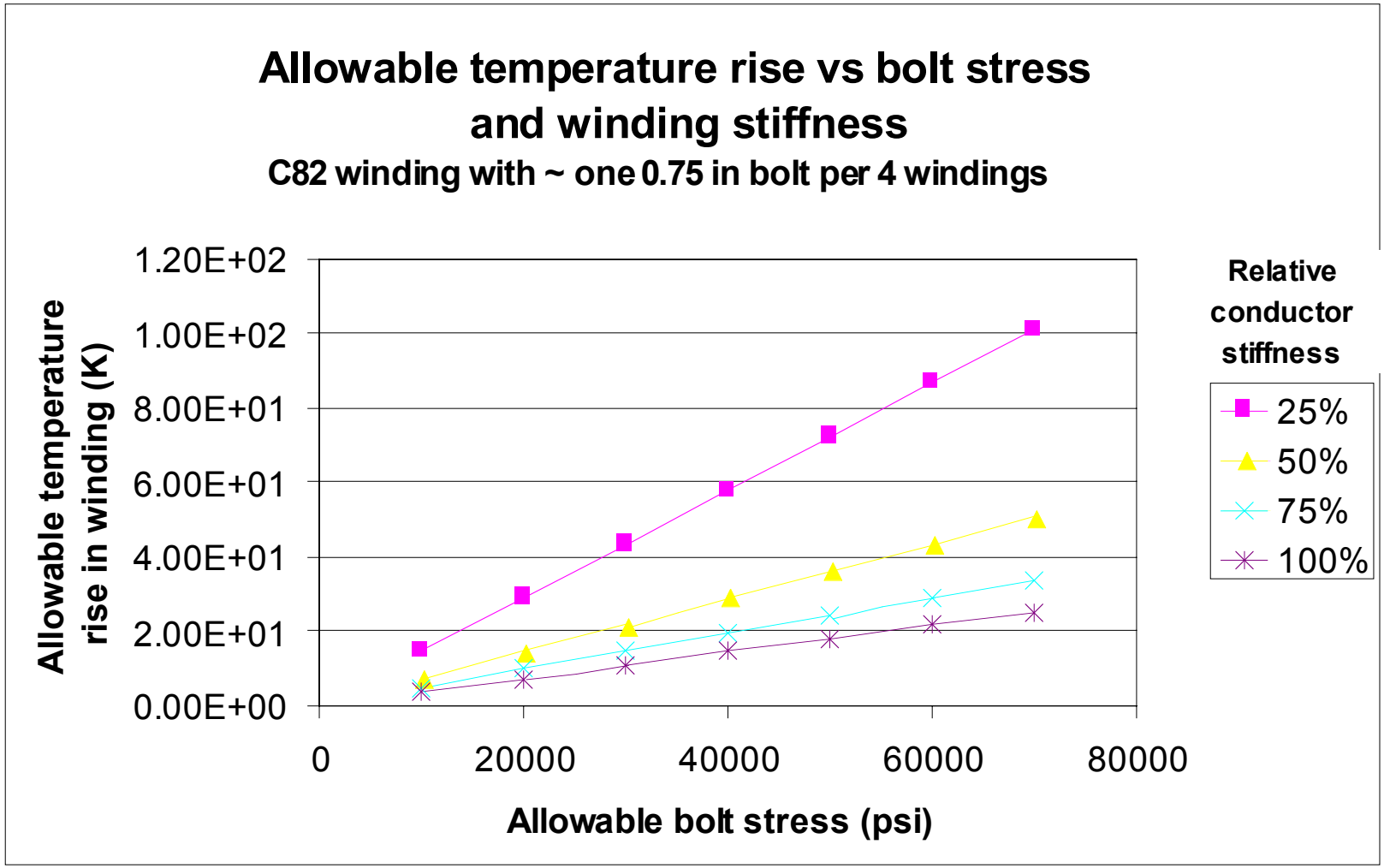
C82 (fd121_16) coil poles are very close together on OB side

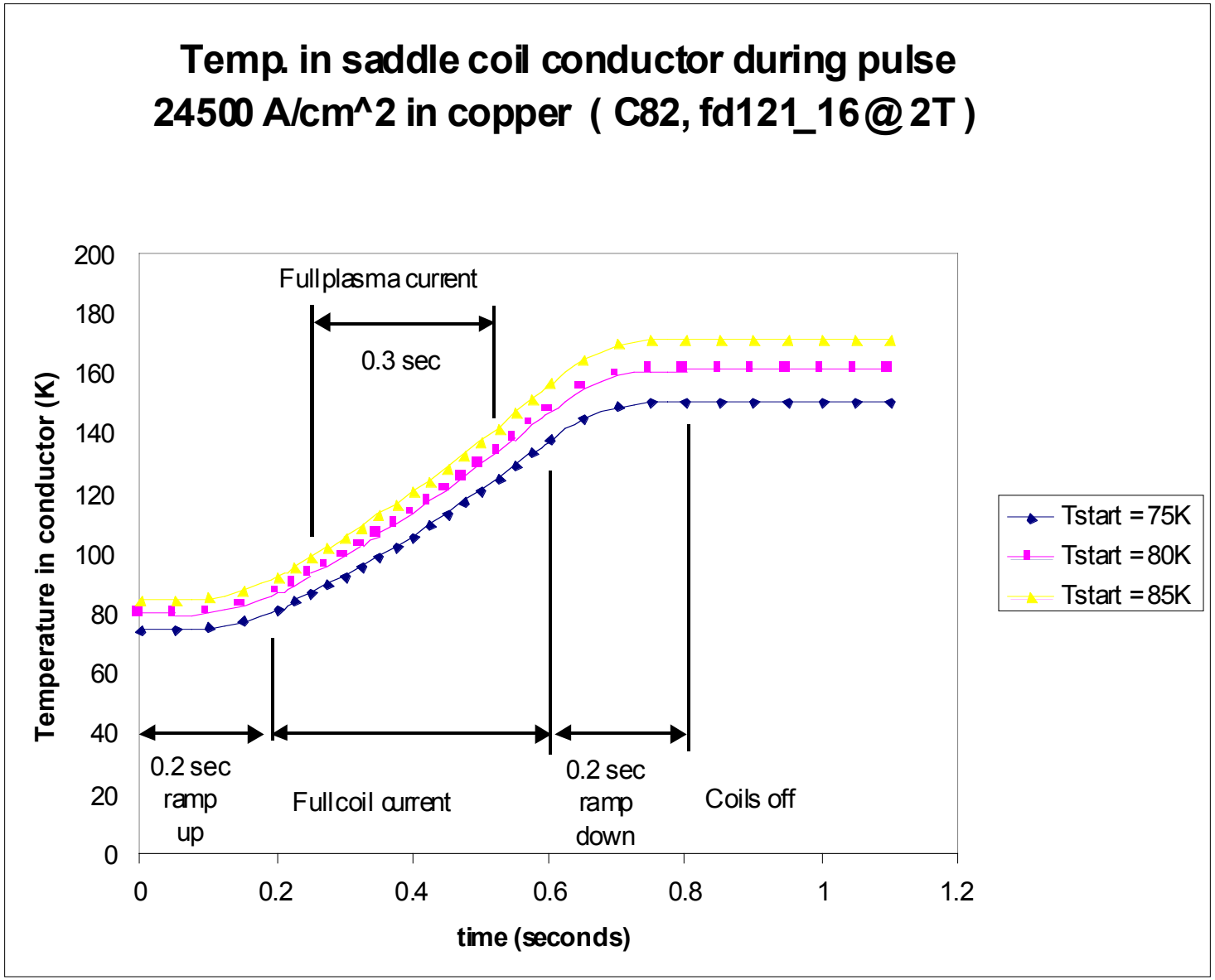



Current density vs number of turns
C82, 91 kAmps per coil, 13 x 70 mm
Braid packing fraction =.75, insul=.037", groundwrap+gap = 0.02"
current density in copper (A/cm^2)
26000
25500
25000
24500
24000
23500
23000
22500
22000
21500
2
6
10
14
no of turns


Temperature vs time, 24500 A/cm^2 in copper
C82, braided conductor, 2T
Temperature (K)
400
350
300
250
200
150
100
50
0
0
1
2
3
ESW pulse length (seconds)
Tstart = 75K
Tstart = 80K
Tstart = 85K
Tstart = 300K
H2O cooled limit

Thermal stress in conductor limits temperature rise, (But smaller C82 windings help)




Temp. in saddle coil conductor during pulse
24500 A/cm^2 in copper (C82, fd121_16@2T)
Temperature in conductor (K)
200
180
160
140
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
1.2
time (seconds)
Full plasma current
0.3 sec
0.2 sec ramp up
Full coil current
0.2 sec ramp down
Coils off
Tstart = 75K
Tstart = 80K
Tstart = 85K

What do we need for PVR?

From January 15 memo by Wayne Reiersen:

- System requirements are defined
- The initial system level design of the stellarator core is complete

  Saddle coil windings, structure, vacuum vessel, axisymmetric coils
- The system level design addresses the technical requirements
- The system level design can be fabricated and assembled
- The stellarator core can accommodate the required ancillary systems
- The system level design meets cost and schedule objectives

How do we get there from here? Near term plans

- Develop self-consistent design for baseline option with C82 coil set
- Solicit more input from vendors and local shops
- Repeat analysis for C82 coil set and latest structural configuration
- Review fabrication and assembly schedule, re-assess schedule risk
- Develop revised cost estimate

What are we still worried about?

Issue	**What helps?**
High current density limits pulse length *Is the pulse length adequate?*	- Move windings closer to plasma - Reduce insulation thickness - Raise temperature limit (needs R&D)
Cost and feasibility of complex saddle coil and shell geometry *Can we build the saddle coils and structure within the budget?*	- Fewer segments - Fewer coils - Wider grooves - R&D
Cost / feasibility of break-bent vessel are not proven	- R&D
Permeability requirements for shell and vessel difficult to achieve	- Quantify effect

Conclusion

Progress has been made since March 30 meeting

- **Selected the baseline design configuration and fabrication concept**

  - Segmented bronze casting with machined grooves for shell fabrication
  - Break-bending of flat developments for vacuum vessel fabrication

- **Coil-plasma separation remains 18 cm minimum**

- **First C82 coil set has been evaluated**

  Coils have higher current density and are more complex than C10

- **Several issues remain, but primary worries are cost and current density**