Saddle Coil Current Density

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PPPL

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Topics

- Uncertainties in J calculation
- Assessment of J in c10
- Comparative assessment of J in c82 and c85
- Conclusions

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Large uncertainties exist in defining achievable J

- **Shell material not yet selected**
  - **The optimum material would have a CTE closely matched to copper**
  - **Reduced thermal stress due to cooldown -> larger ΔT during pulse can be tolerated**
  - **Strongly favors a bronze shell over a plastic shell (better CTE, no thermal shim)**
  - ***For this study, a brass shell was assumed***
- **Mechanical properties of conductor unknown**
  - **Testing planned to determine modulus and stress limit of cabled conductor**
- **Detailed analyses using these properties/limits not done**
  - **Allowable temperature rise unknown**
  - ***ΔT=100°C assumed***
- **Currents not available for full scenario or range of flexibility**

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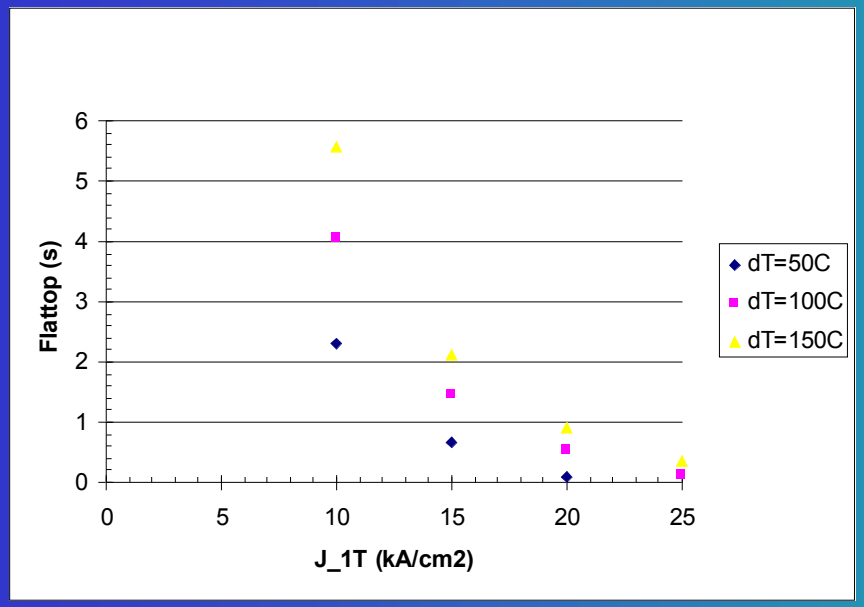
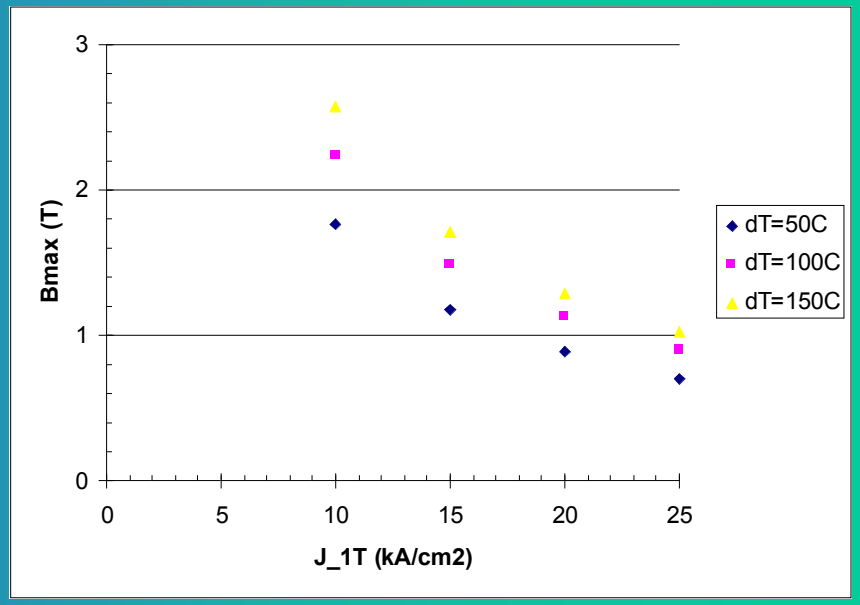
J _ 1T is a useful metric

- **It defines the flattop at 1T for a given ΔT**
- **It places an upper bound on B for a given ΔT**
- ***J_1T < 15 kA/cm² is necessary to achieve a >1s FT at 1T and B>1.2T for a 0.3s* FT**





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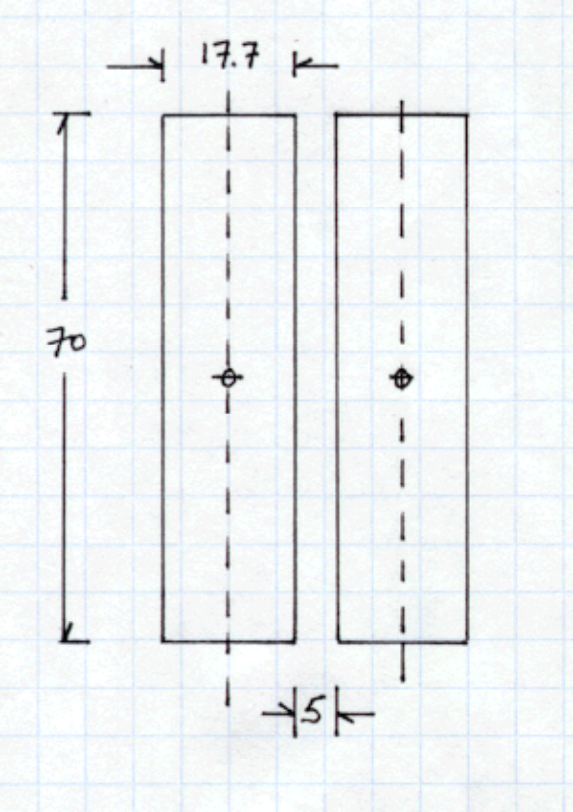
J in c10 previously assessed assuming parallel windings

- Neglected curvature in CCS
- Results in modest J_1T (9 kA/cm^2) with a 5mm ligament between coils
  - 17.7mm x 70mm winding cavity
  - 5.0s FT at 1T, 0.3s FT at 2.45T for ΔT=100°C



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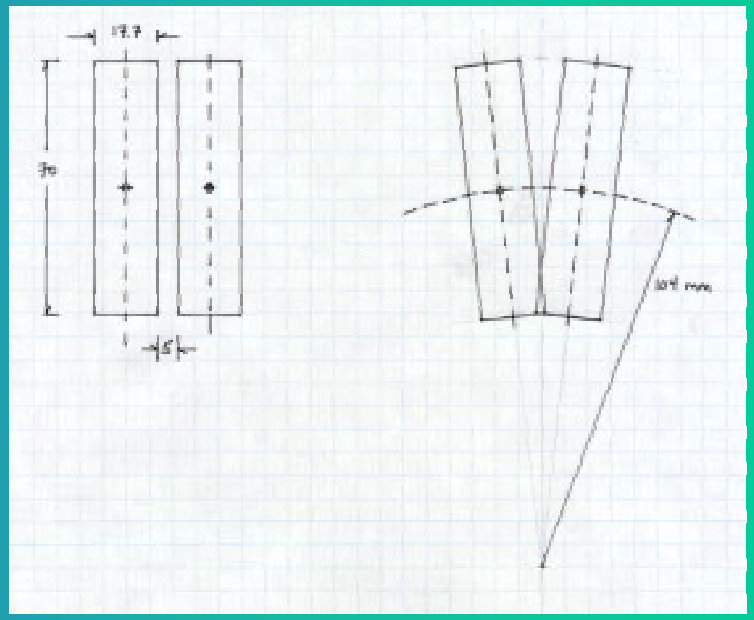
c10 windings not parallel

- Adjacent windings converge at 0.218mm/mm
- Equivalent radius of curvature is 10.4cm, ~60% of the 18cm offset
- Results in interference for a 70mm deep winding



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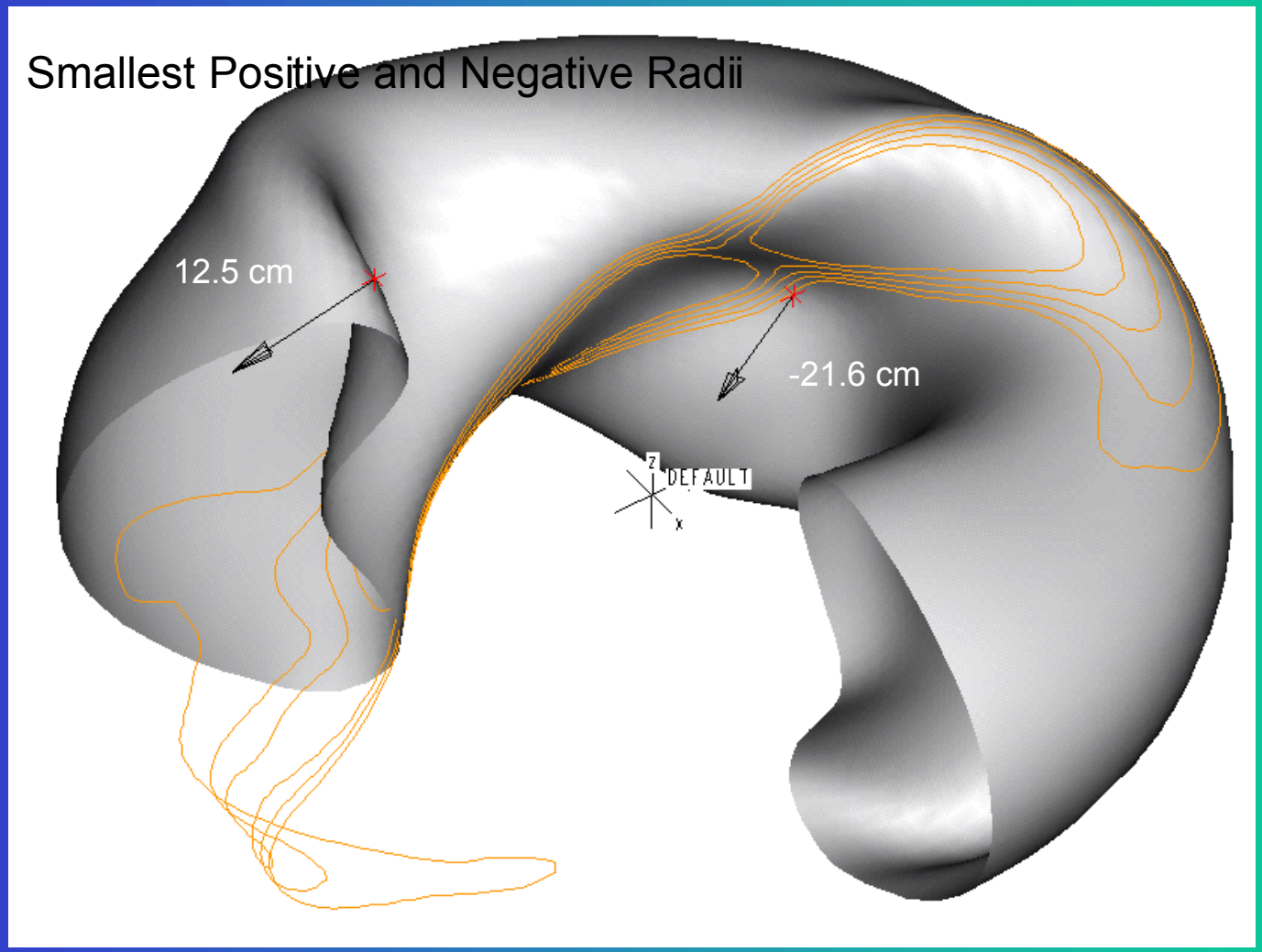
Pro/E analysis of CCS confirms tight curvature in cuspy region



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Restoring 5mm ligament requires smaller winding

- **17.7mm x 70mm -> 11.2mm x 59.3mm**
- **J_1T increases from 9 kA/cm^2 to 23 kA/cm^2**
- **The FT at 1T would be about zero**
- ***However, no J optimization done for the c10 coil design presented here***

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Bunching conductors proposed to relieve J constraints

- Eliminates ligaments between conductors in region of highest J
  - eliminates machined reference for placement of winding
  - eliminates lateral support
  - degrades thermal contact with bronze shell
  - feasibility questionable
- Potentially could reduce J from 23 kA/cm^2 to 11.5 kA/cm^2, putting us "back in the box"

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Two c82 coil designs studied

- **Both coil designs optimized for minimum J**
- ***Assumed local curvature of 10.4 cm (c10 value)***
- **sad18ef.10 -- the better fit option with higher J**
  - **max/mean separations of 18mm/3.4mm**
  - **cannot be implemented with 5mm ligament -- J_1T = 252 kA/cm^2**
  - **virtually no FT at 1T with no ligament -- J_1T = 22 kA/cm^2**
- **sad18.16a -- the looser fit option with lower J**
  - **max/mean separations of 29mm/7.9mm**
  - **physics acceptability TBD**
  - **still out of the box with a 5mm ligament -- J_1T = 24 kA/cm^2**
  - **marginally acceptable if ligament can be eliminated -- J_1T = 12 kA/cm^2**

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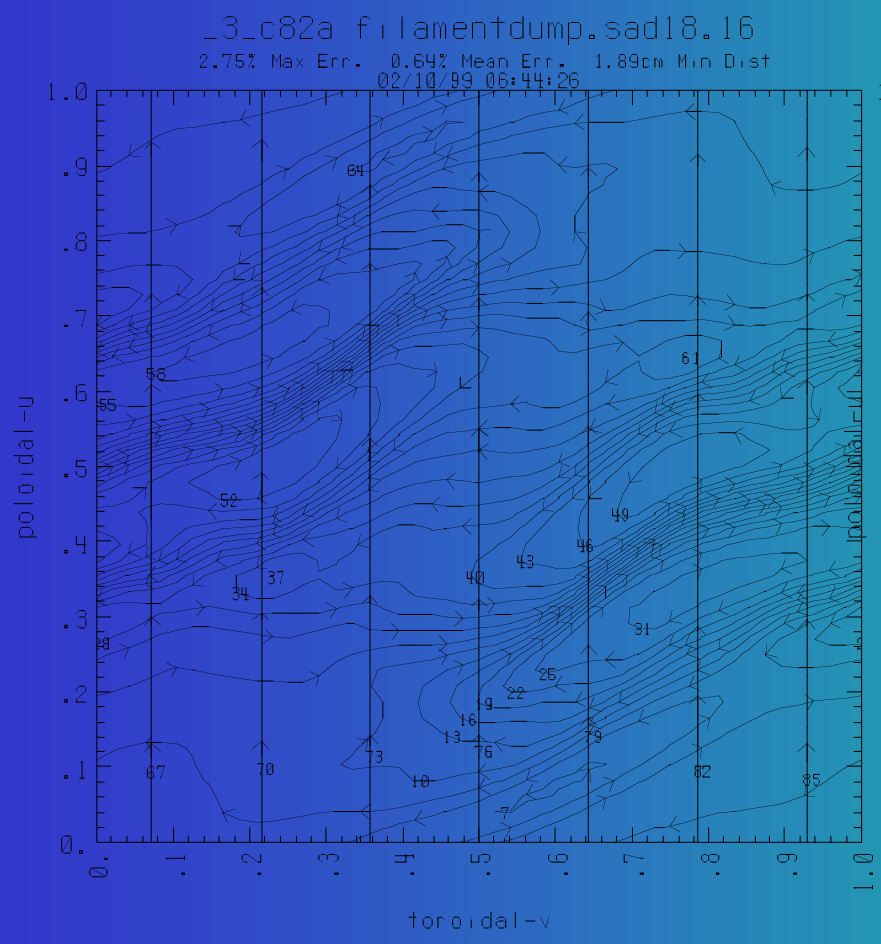
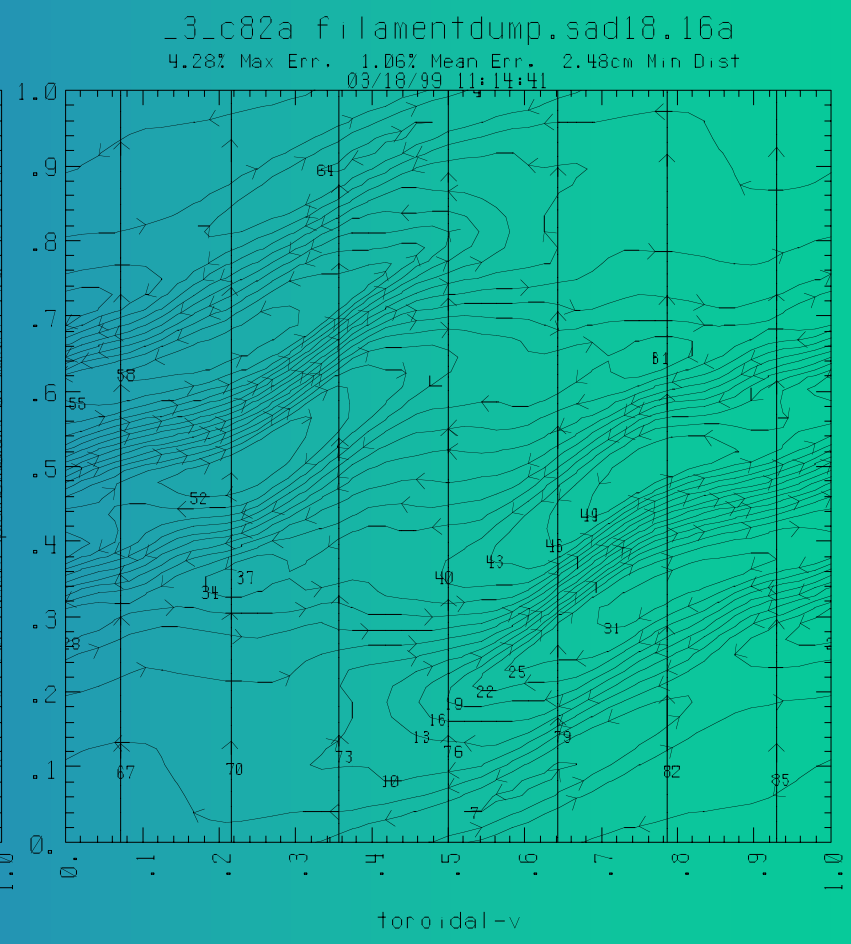
c82 coils were manually spread out to reduce J in sad18.16a





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Two c85 coil designs also studied

- Again, both designs optimized for minimum J; c10 curvature assumed
- sad18ef.16 -- the better fit option with higher J
  - max/mean separations of 23mm/3.4mm
  - out of the box with 5mm ligament -- J_1T = 27 kA/cm^2
  - marginally acceptable with no ligament -- J_1T = 12 kA/cm^2
- sad18ef.16a -- the looser fit option with lower J
  - max/mean separations of 35mm/5.8mm
  - physics acceptability TBD
  - marginally acceptable with a 5mm ligament -- J_1T = 13 kA/cm^2
  - ample margin with no ligament -- J_1T = 8 kA/cm^2

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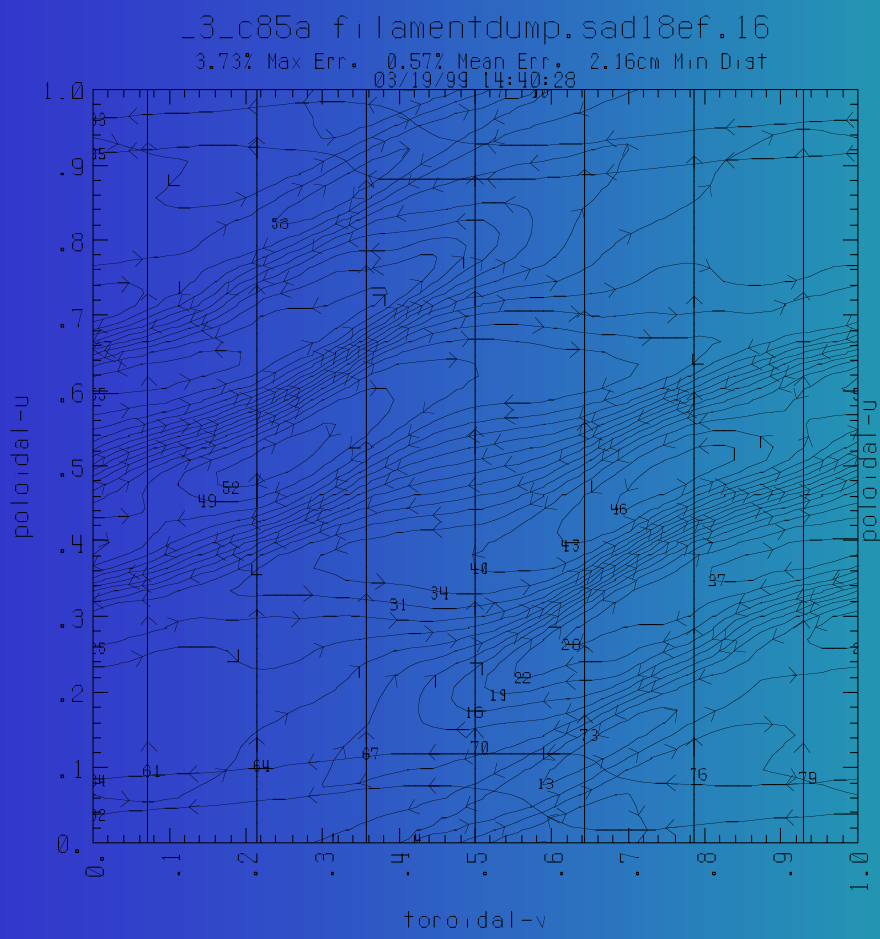
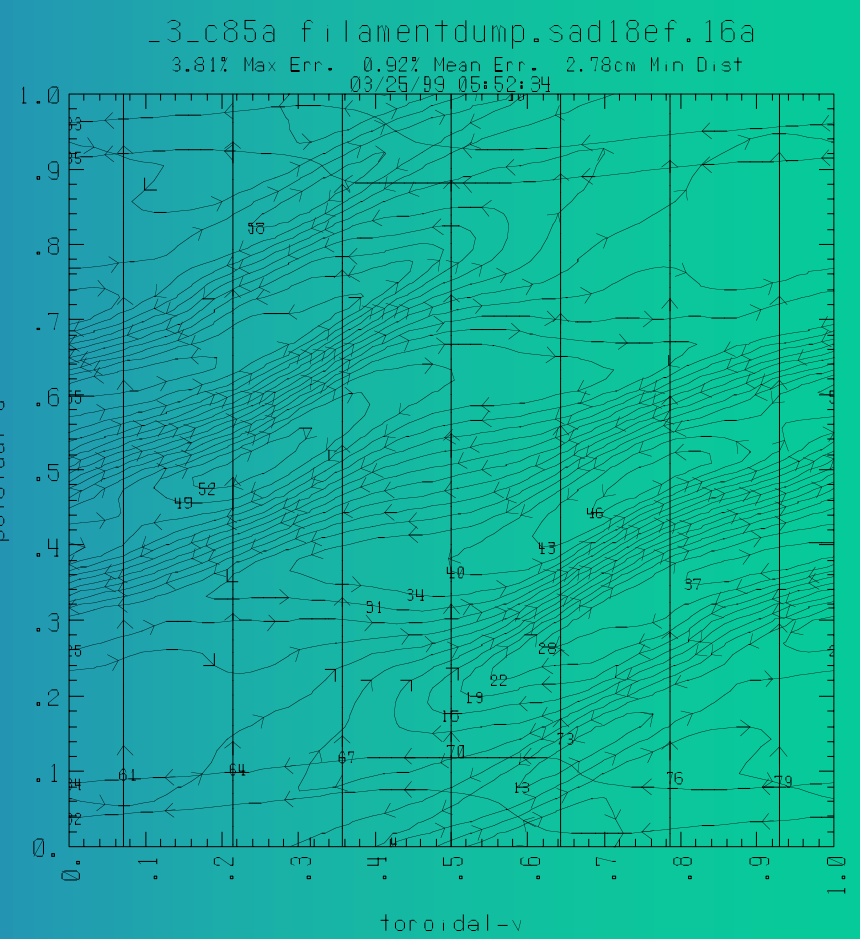
c85 coils were manually spread out to reduce J in sad18.16a





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c82 coil designs consistently feature substantially higher J

- J_cu is typically 50-100% higher in c82 than c85
- Reduces 1T FT times by 50-75%, B_{max} by 30-50%
- More constraining in physics design
  - Only loose fit gets in the box for high beta, high current snapshot
  - Other snapshots in reference scenario not yet studied
  - Promises less flexibility in B, β, I_p, $\iota(r)$
- More constraining in engineering design
  - Limits design options, decreasing the likelihood of finding a solution

Fit	Ligament	J_c82	J_c85	J_c82/J_c85
Good -- mean separation 3-4 mm	5mm	252	27	9.4
	None	22	12	1.8
Loose -- mean separation 6-8 mm	5mm	24	13	1.9
	None	12	8	1.5

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Conclusions

- c85 has superior robustness to uncertainties in coil current requirements and coil design relative to c82
- Including Js in optimization resulted in a major improvement
  - J in c85 is 30-50% lower than in c82
  - Optimizations should include curvature too when targeting Js
  - Optimizations should be continued with high priority
    - Js in c82 is very high -- makes coil design difficult and renders CS vulnerable to criticism on reactor relevance
    - Alternatives -- explore configurations intermediate to c82/c85? higher A? reactor relevant configurations?

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Conclusions (2)

- New tools developed by coil design group also resulted in substantial improvements
  - J in c82 went from being 2x c10 to 1x c10
  - Additional work required to
    - define coil currents for other operating points
    - account for surface curvature in CCS when targeting J
    - examine utility of auxiliary coils for reducing J
- Engineering group should proceed with
  - defining the configuration for the stellarator core
  - R&D to establish mechanical properties and limits for cabled conductor
  - a 3D study of the c82 (sad18.16a) coil design to maximize J and assure the geometry is reasonable

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Conclusions (3)

- Options for increasing achievable J need to be aggressively explored
  - GHe cooling of shell down to 30K would allow longer pulse lengths
    - CTE and $dT/d(J^2t)$ decrease
    - BUT it adds the cost of a refrigerator and negatively impacts rep rate
  - SC coils will be explored with MIT