Winding Pack Design

Presented by Brad Nelson

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NCSX project meeting

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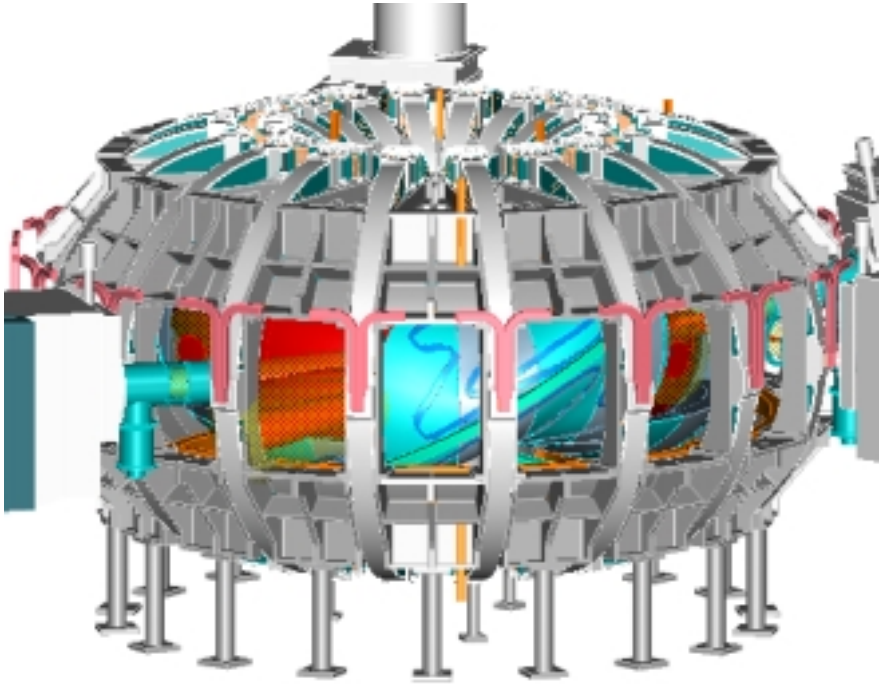
Presentation Outline

- **For the two options:**
  - Saddle coils
  - Modular coils

- **What are requirements / constraints?**
- **What is baseline winding pack?**
- **Does winding pack meet constraints?**
- **Remaining issues**

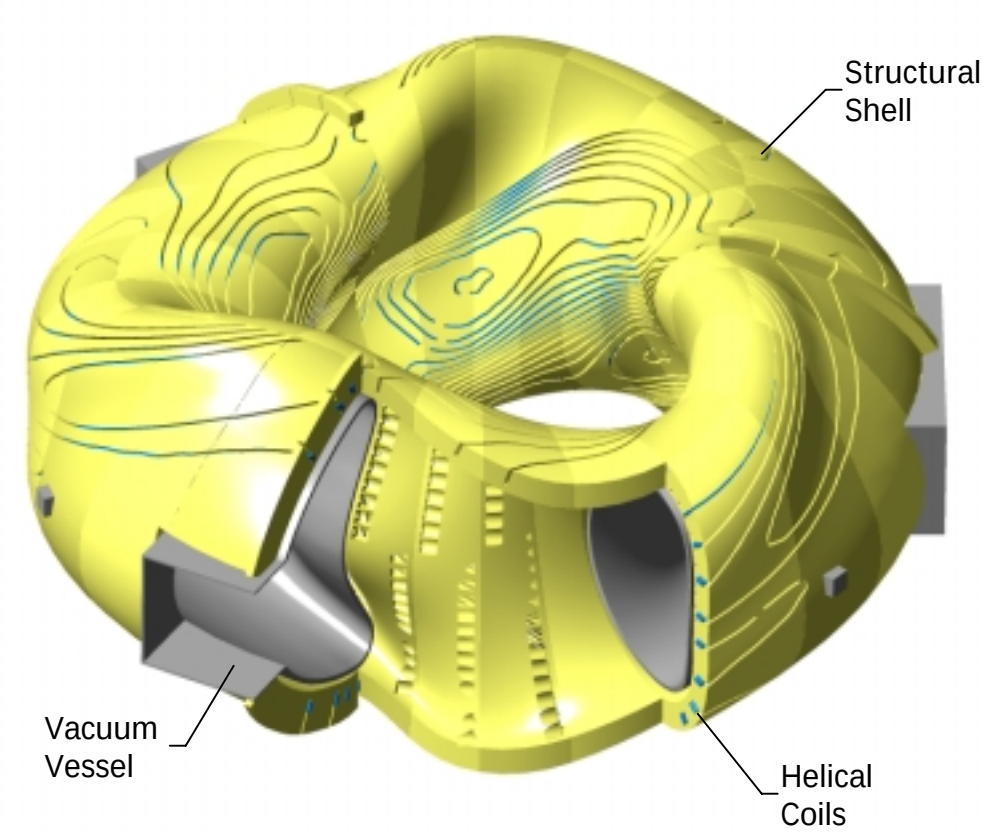
Saddle Coil Option

- **Saddle Coil set li383s_r1**
- **24 saddle coils, 4 types**
- **1/R background field of 2T**
- **6 pairs of PF coils**

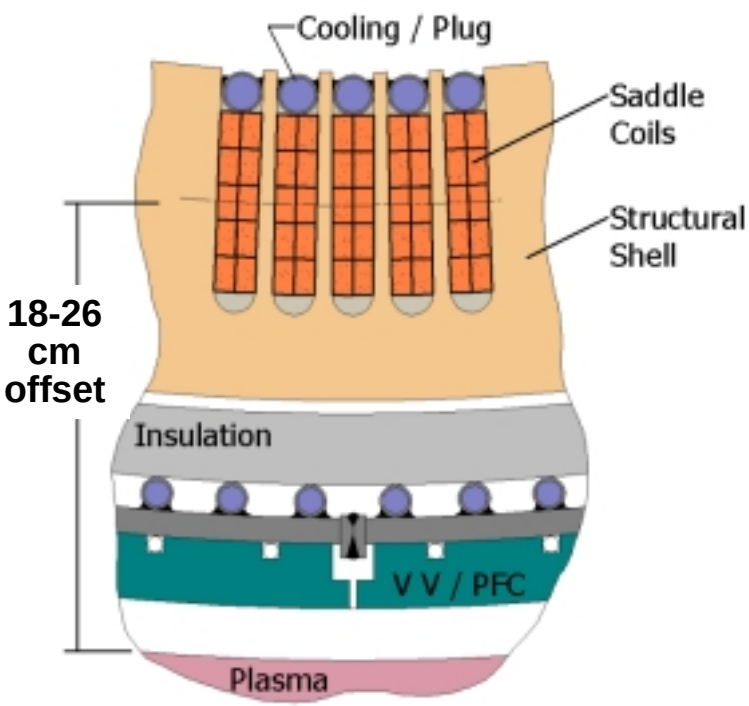


Saddle coils wound on shell

- Cast Nickel-Al-Bronze structure, 48 segments, ~1-in wide x 3.5-in deep slots



Core Assembly



Typical Coil Cross-Section

Saddle coil design criteria

- **Conductor is flexible, cable type conductor**
  - **Continuously supported by structure**
  - **no cooling during pulse**
  - **10 minutes maximum cooldown time**
  - **Operation at cryogenic temperatures is allowed for saddle coils**

Coil designed for reference scenario (2T, ~.6 s ESW)

- **Winding must meet limits on:**
  - **Current density**
  - **Bend radius**
  - **Shell groove dimensions**

Winding design criteria

- **Current density is the primary issue**

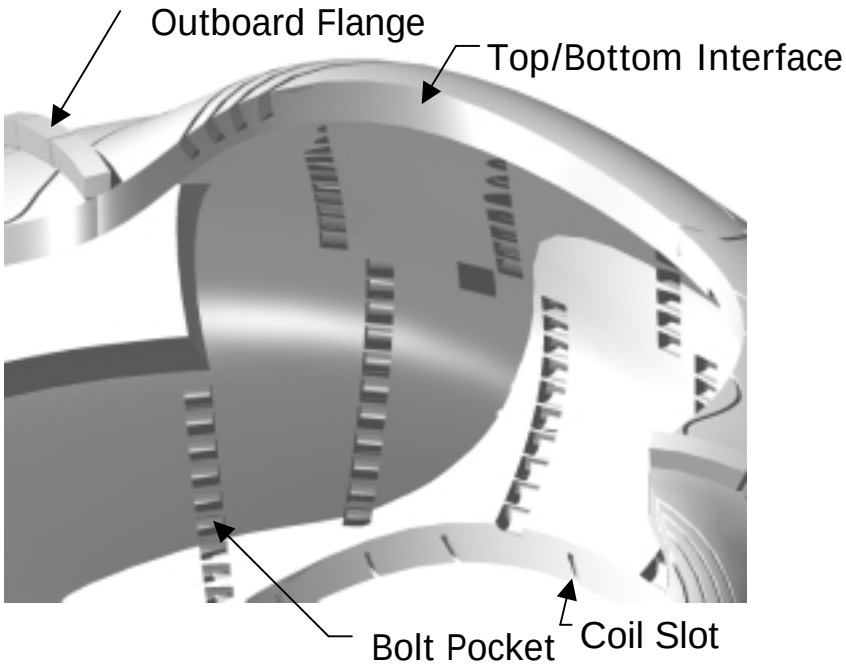
- **Current density is limited by a number of factors**
  - **material temperature limits**
  - **thermal stress due to temperature rise**
  - **power consumption**
  - **cooldown and pulse repetition rate**
  - **fatigue, other effects**

- **Tentative limits on current density *for Ref. Scenario* are:**

Cooling option	Temp range	Current density limits in Cu
Room temp	27 to ~ 60 C	~ 10 kA/cm^2
Refrigerated	10 to ~ 60 C	~ 12 kA/cm^2
Cryogenic	85 to < 185 C	~ 22 kA/cm^2

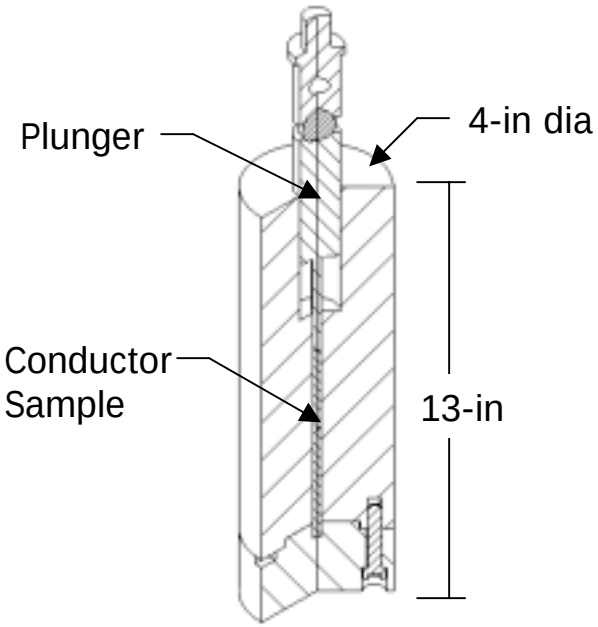
How hot is too hot?

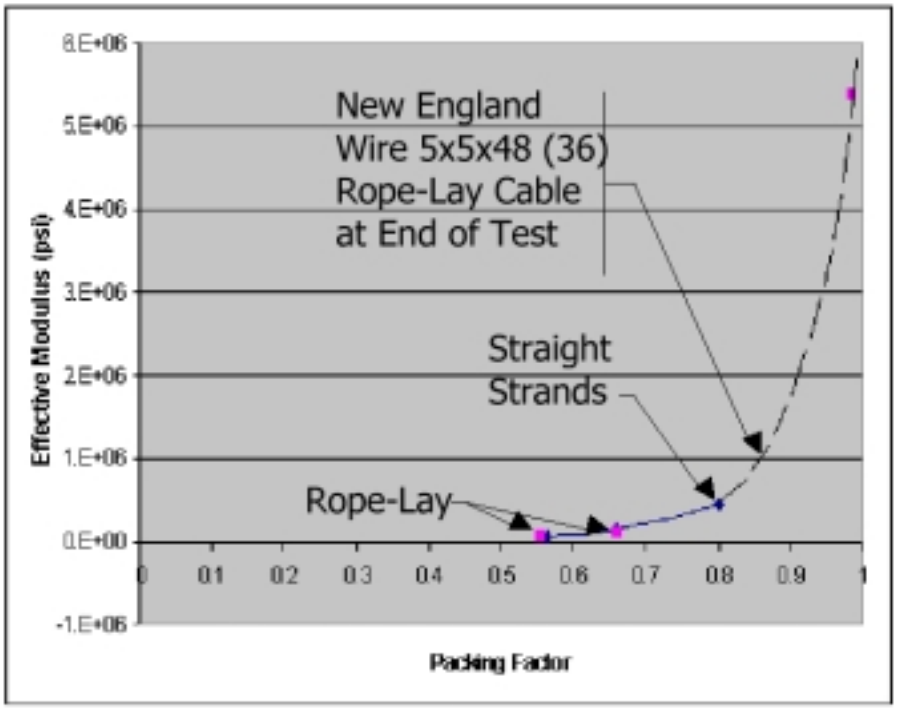
- **Thermal stress was considered primary limit**
  - Thermal stress in shell depends on winding spacing, bolt spacing and stiffness of winding
  - Stiffness of winding is the primary factor, “stiff” conductor would limit temp rise to < 20K current density to < 10 kA/cm^2
- **Big advantage if we can eliminate bolts**



R&D shows cable is soft

- **Tests show cable soft enough to allow 250K rise**

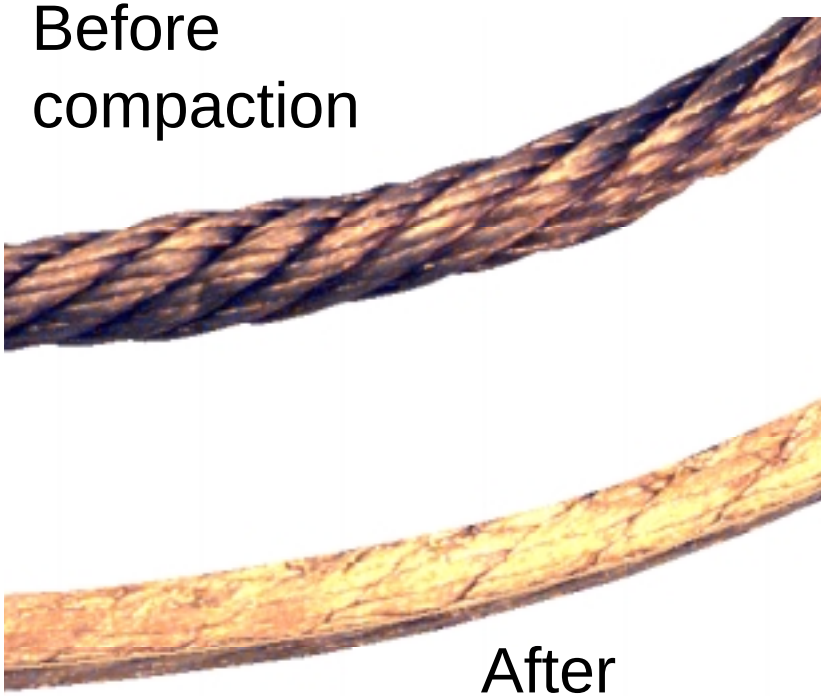




- **Current density target set at <20 kA/cm^2 in copper** ***considering all factors***

What is 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**

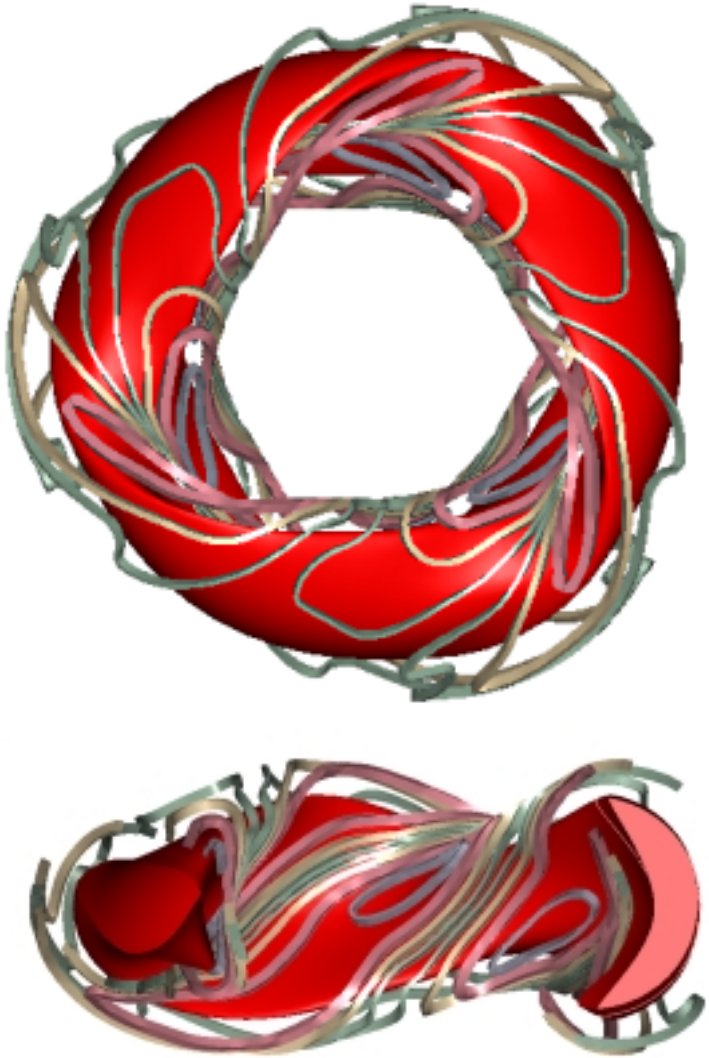


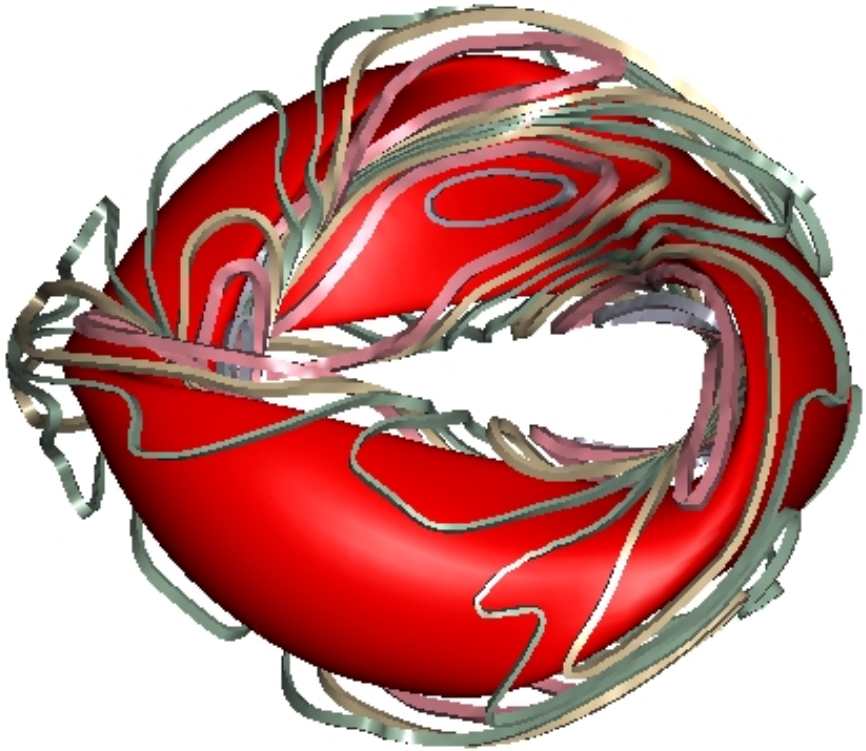
Design criteria summary

- **"In-PBX" studies provided insight for design of saddle coil windings**
  - **Current density limit of 22 kA/cm^2 in copper (LN cooled)**
  - **Bend radius limit of 3 x conductor width**
  - **Winding groove > 13 mm for machining**
  - **Winding spacing depends on current in winding (ie, loads on ligament)**
- **Criteria used to develop / optimize new options**

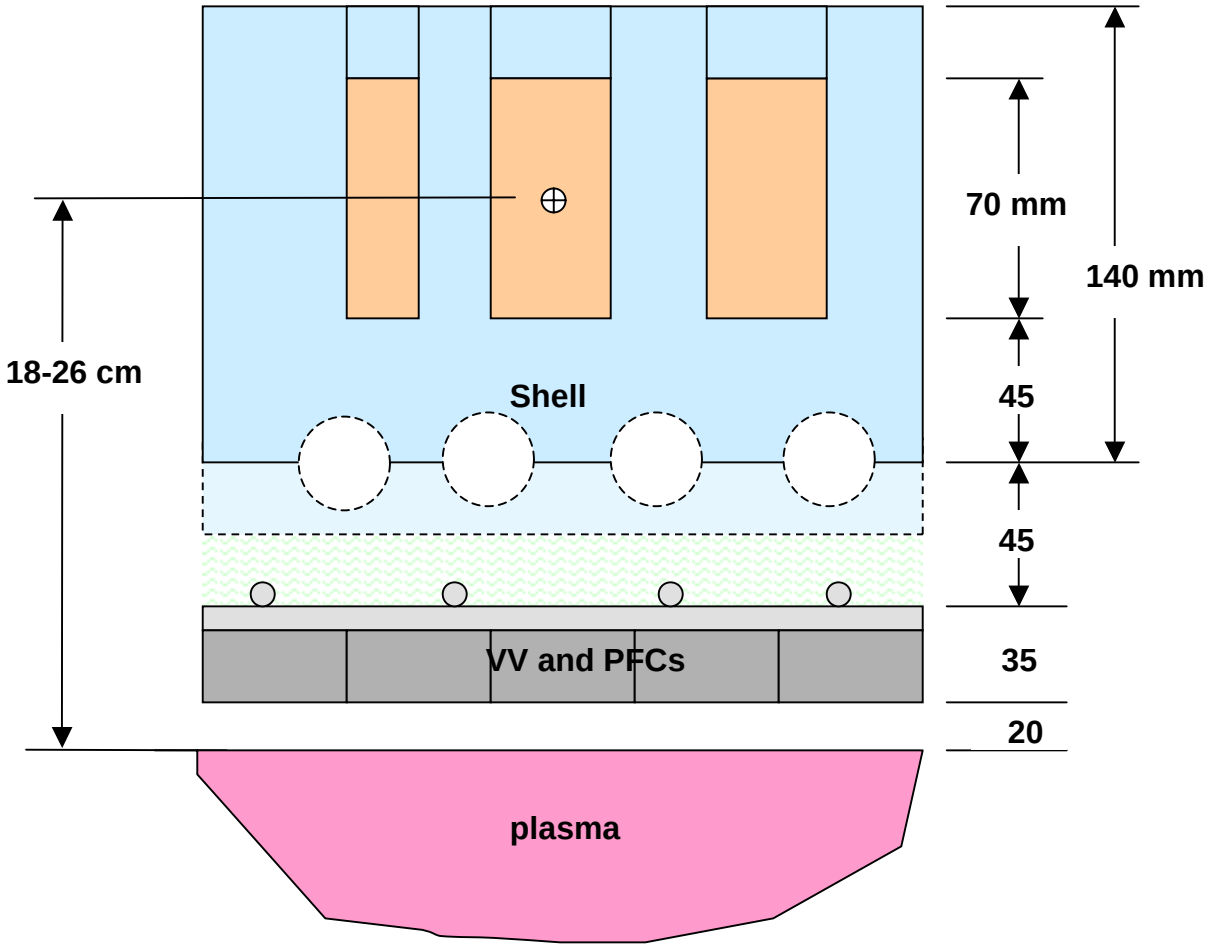
LI 383S_r1 Coil configuration

- **6 sets of 4 coil types**



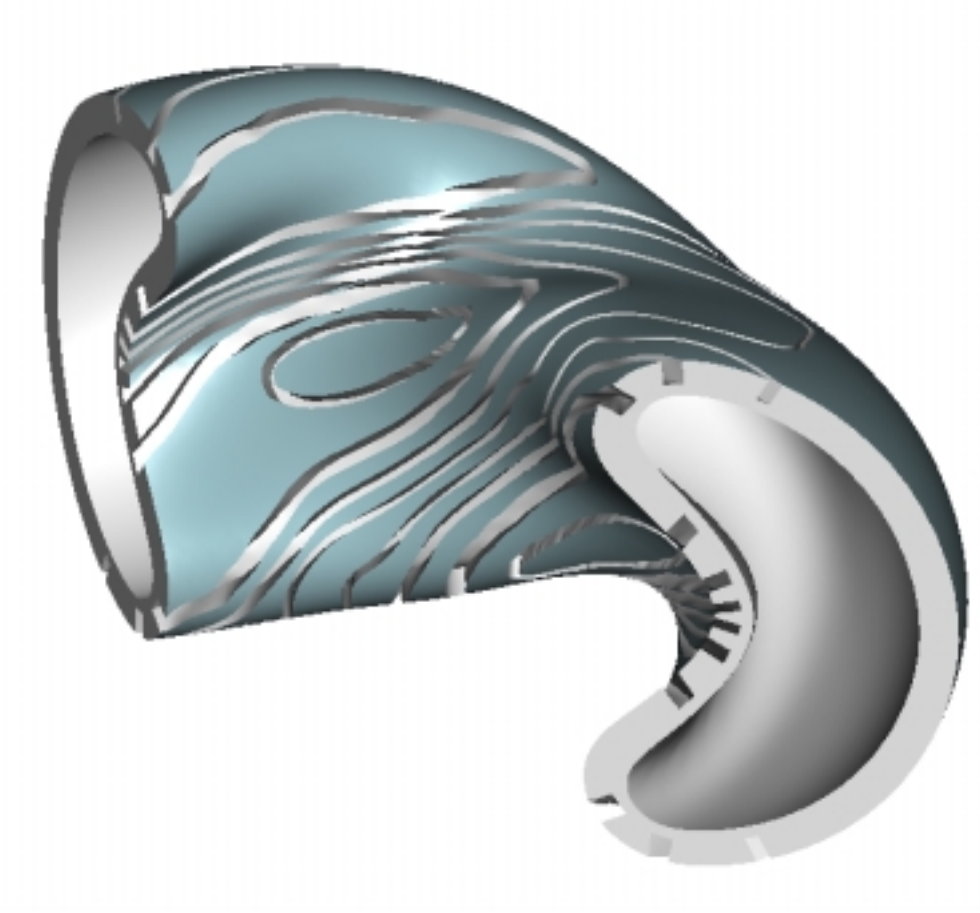


Nominal winding space



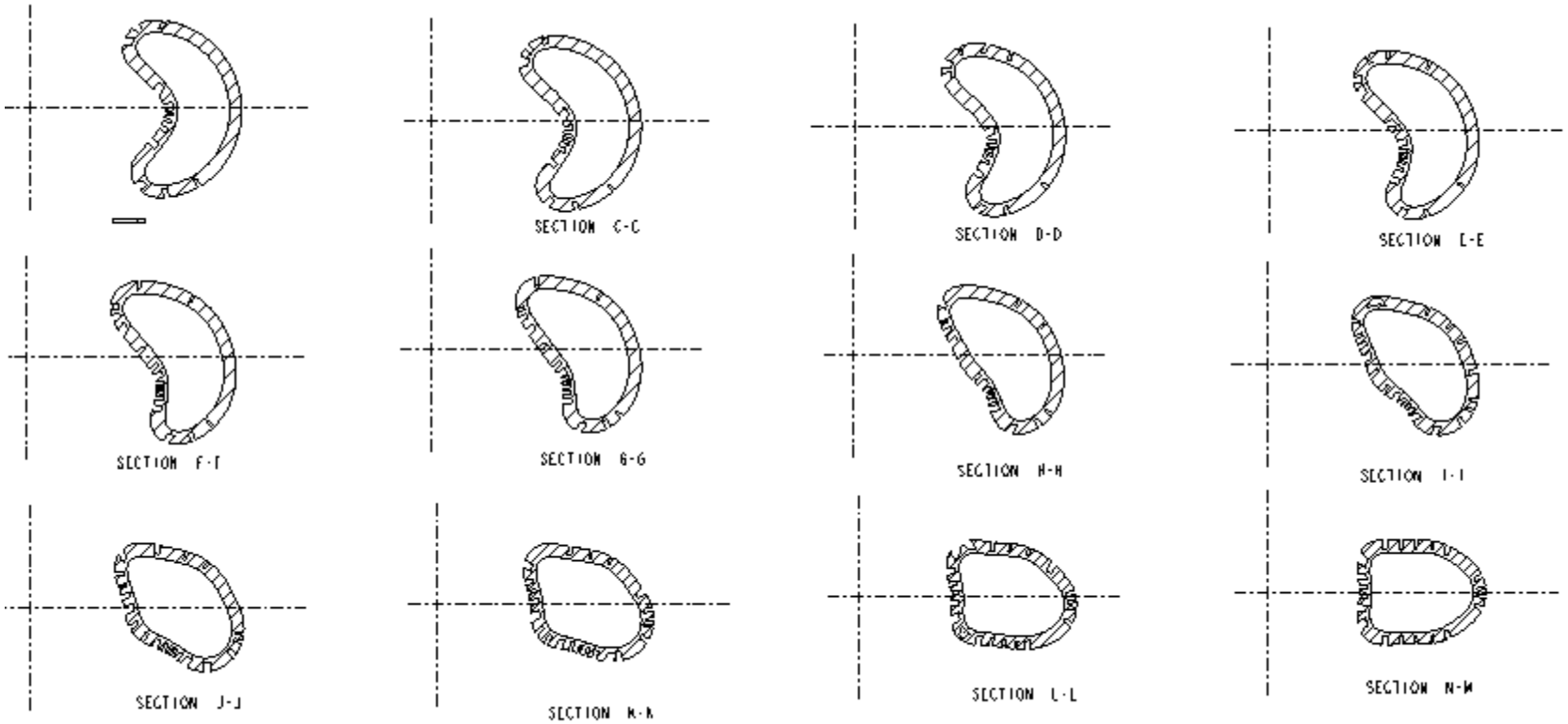
Shell groove dimensions

- **Grooves for windings**
  - **Must provide accurate winding slot**
  - **Should not interfere with each other**
  - **must provide adequate lateral structure**



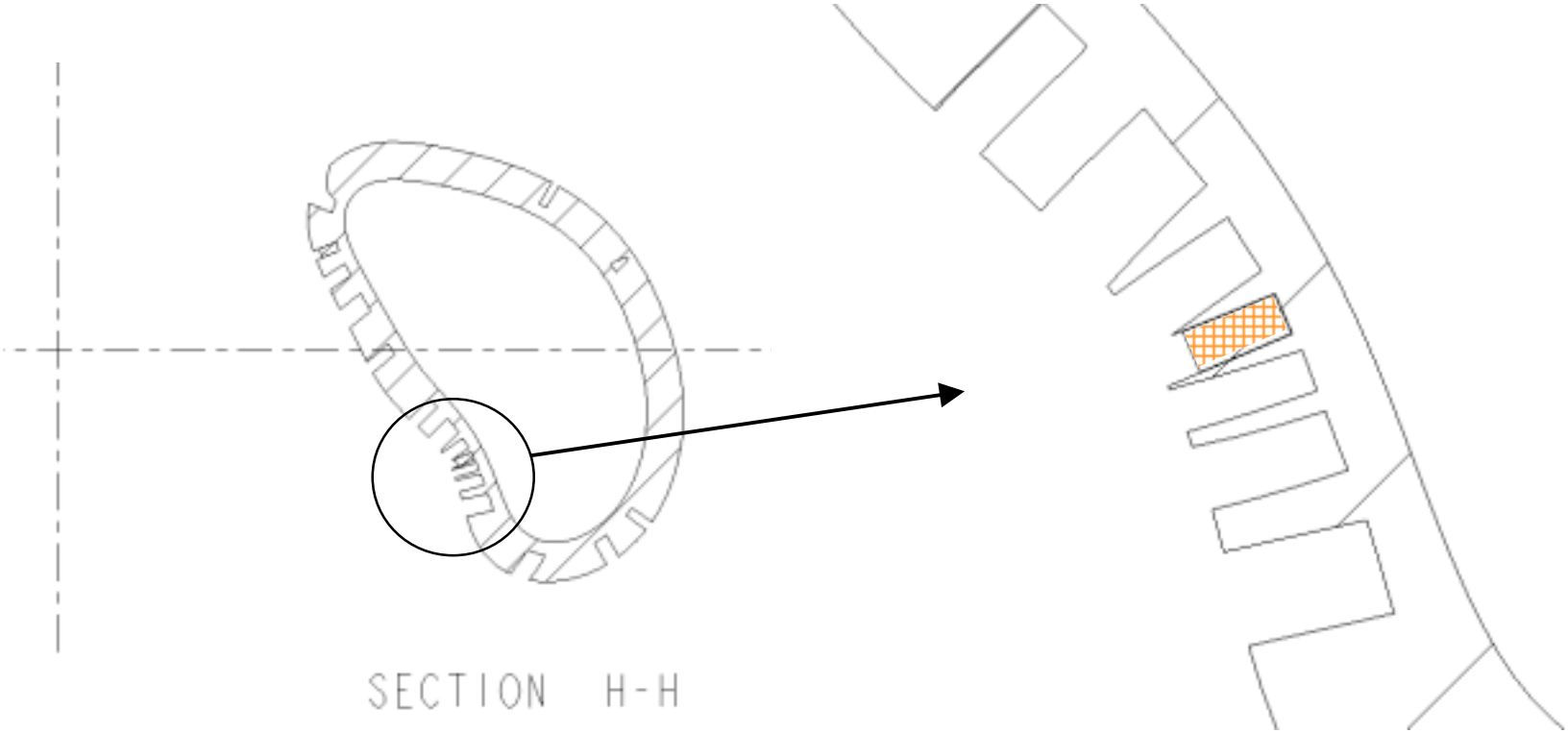
Shell groove dimensions

- **Each section must be checked**



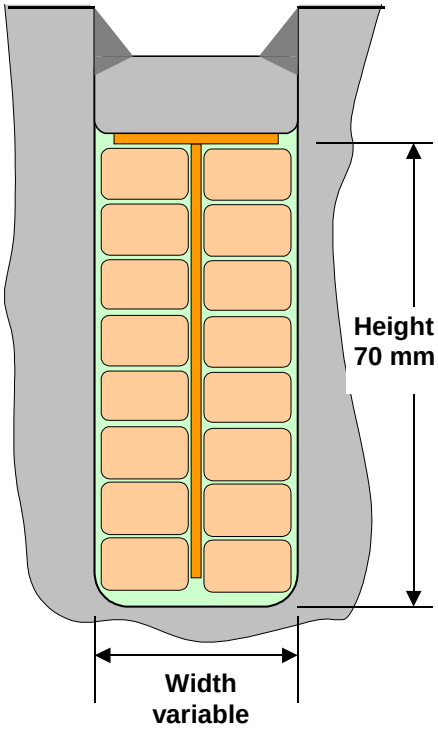
Max slot width not obvious

- **Shape and thickness of ligaments vary considerably**



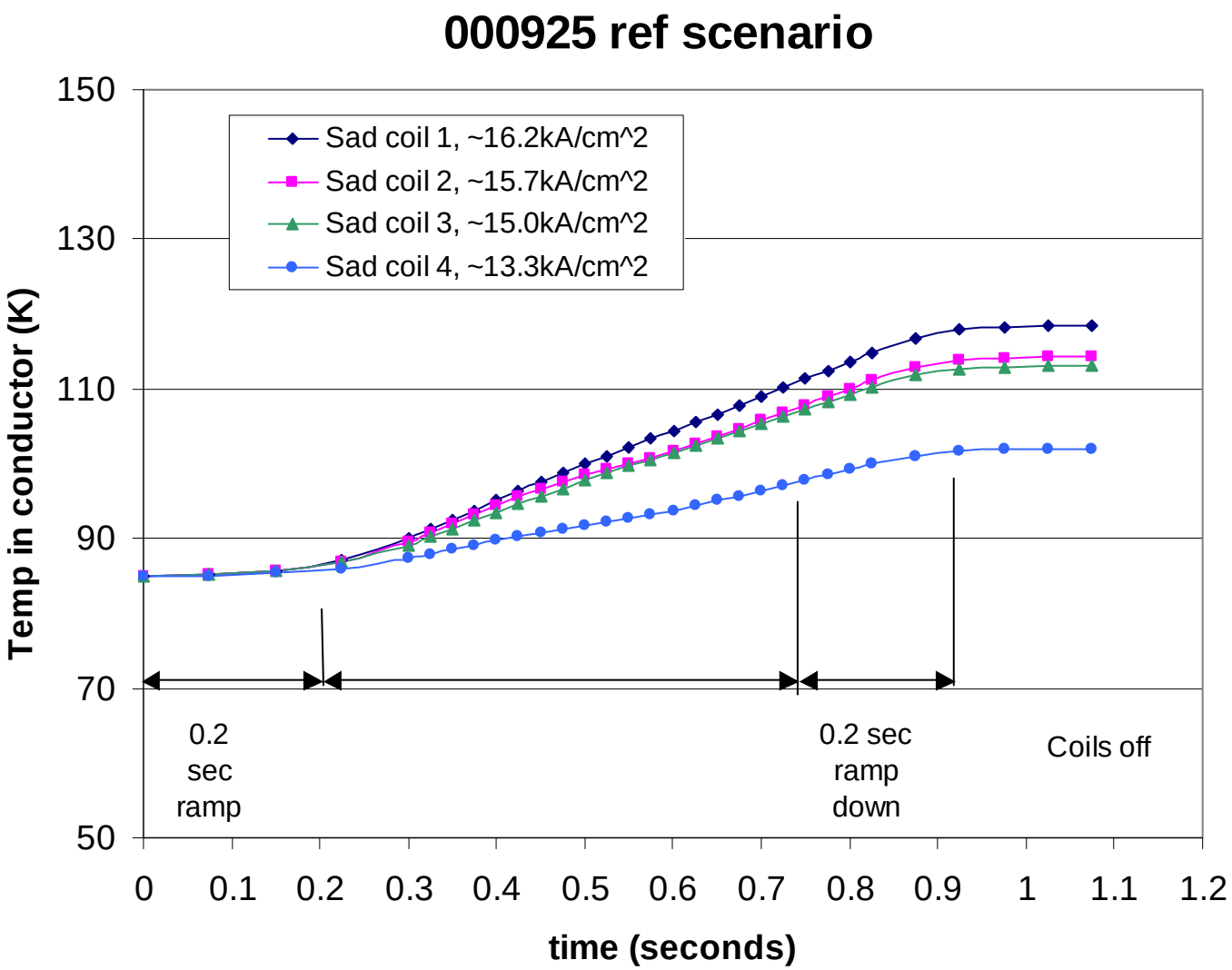
Li383 Saddle coil parameters

	Coil 1	Coil 2	Coil 3	Coil 4
No. of coils	6	6	6	6
Nominal current per coil (kA)	149.5	219.3	332.7	185.9
Number of turns per coil (w x h)	2 x 8	2 x 10	4 x 8	2 x 10
Current per turn (kA)	9.34	10.97	10.40	9.30
Length per turn (m)	15.07	10.96	7.64	2.16
Conductor bundle width (mm) height (mm)	 30 70	 44 70	 68 70	 44 70
Ground insulation thickness (mm)	1.5	1.5	1.5	1.5
Turn insulation thickness (mm)	1.5	1.5	1.5	1.5
No x thick of cooling septa (mm)	1 x 2	1 x 2	2 x 2	1 x 2
Copper cable packing fraction	.7	.7	.7	.7
Conductor current density (kA/cm^2)	16.0	15.5	14.8	13.2
Nominal oper. starting temp (K)	85	85	85	85
Temp rise for ref scenario (K) *(Limit = 100 K)*	33	29	28	17
Peak resistive power per coil (MW)	1.8	1.7	1.7	0.2

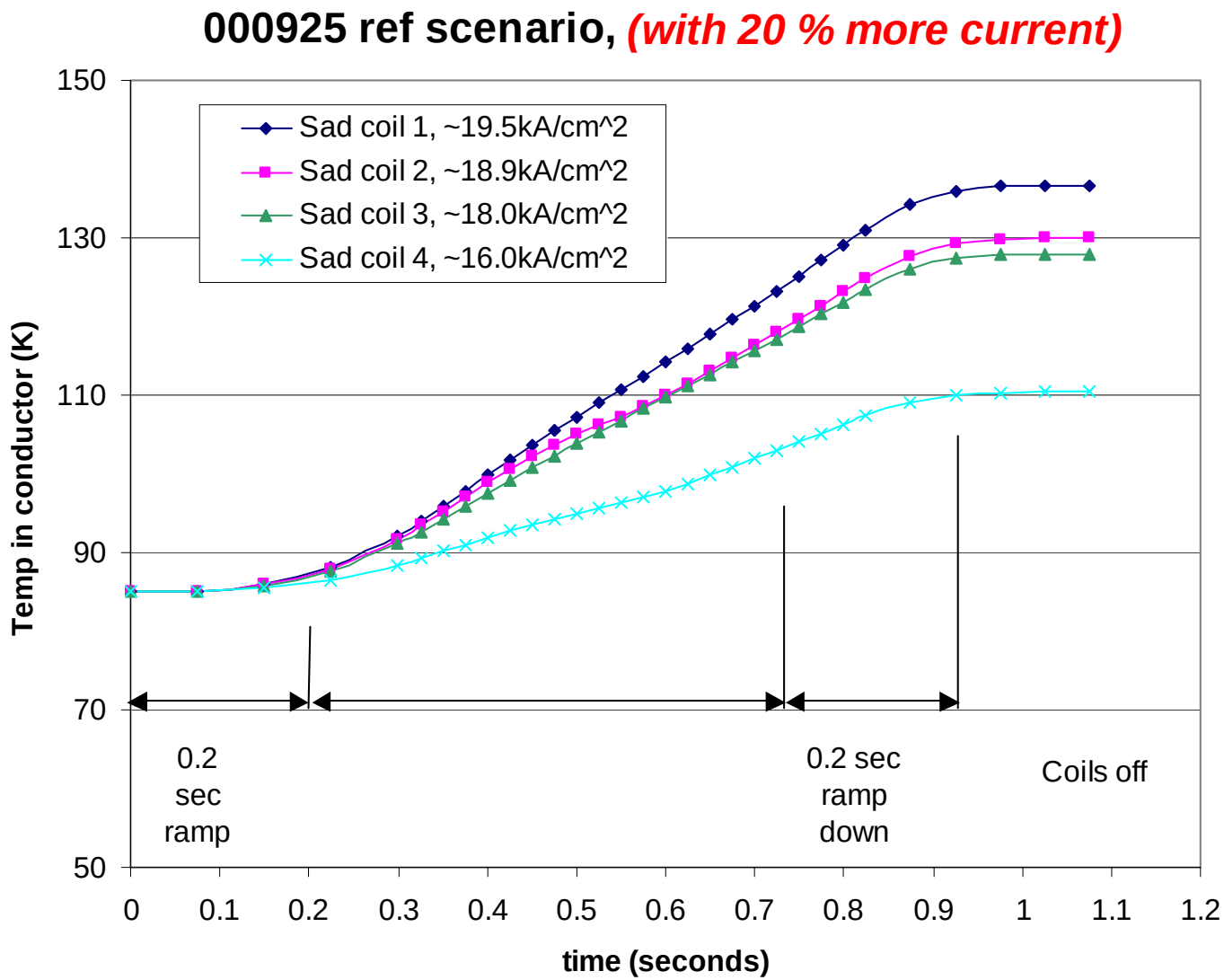


32 MW/coil set

Temperature rise during shot

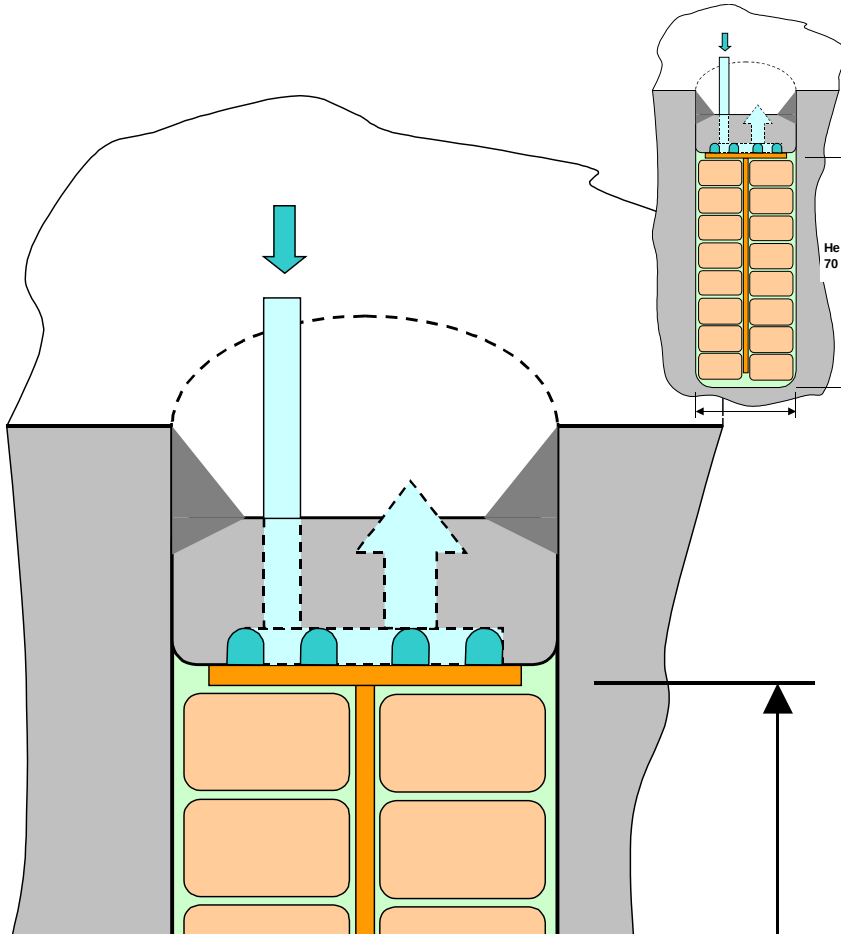


Temperature rise during shot (2)



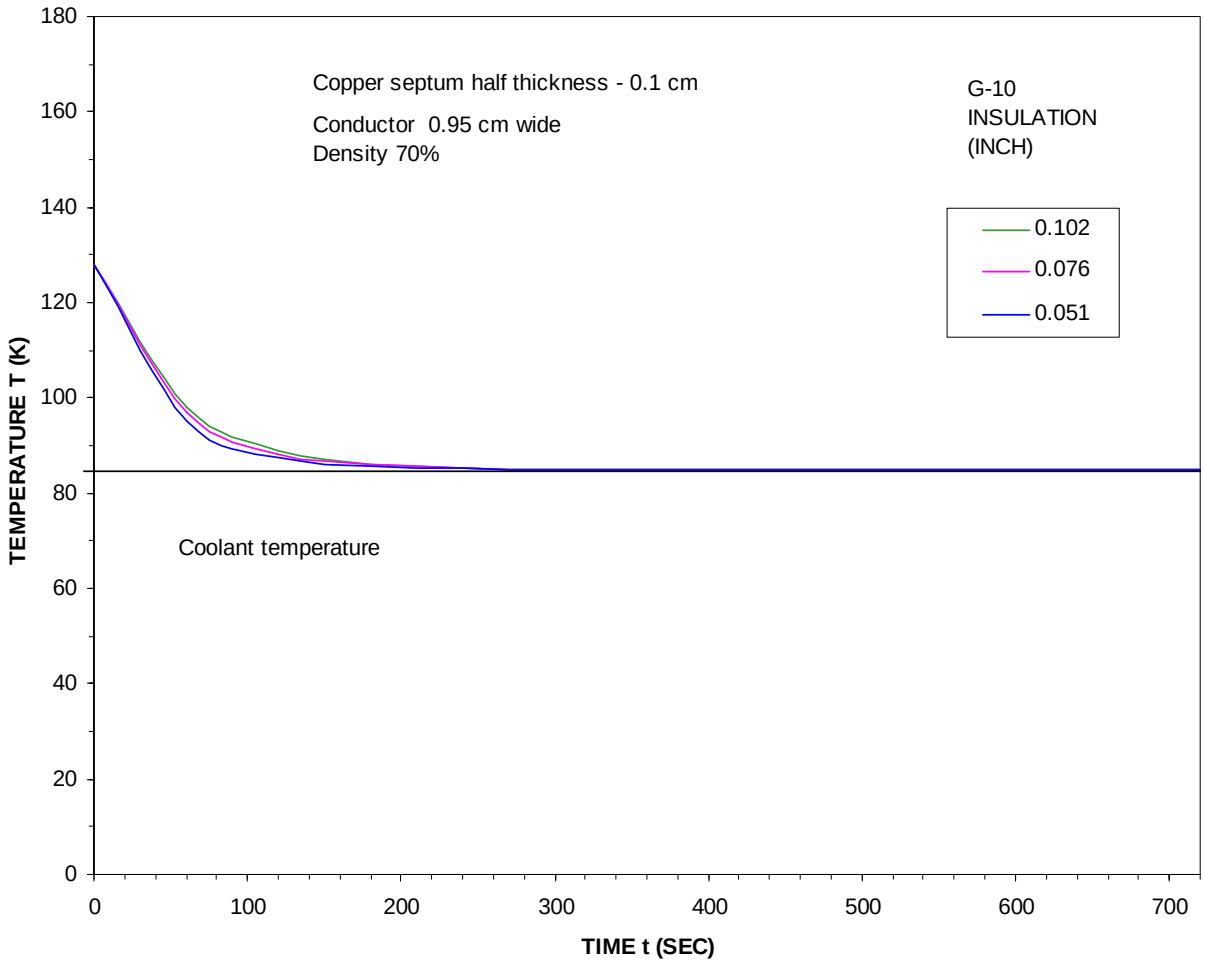
Coil cooling between shots

- **Conductor must be cooled in 10 minutes from full power shot**
- **N2 Gas cooling of septum is baseline option**
- **Gas flows into passages and out between winding retainer blocks**
- **Passage above winding captures gas within cryostat insulation**



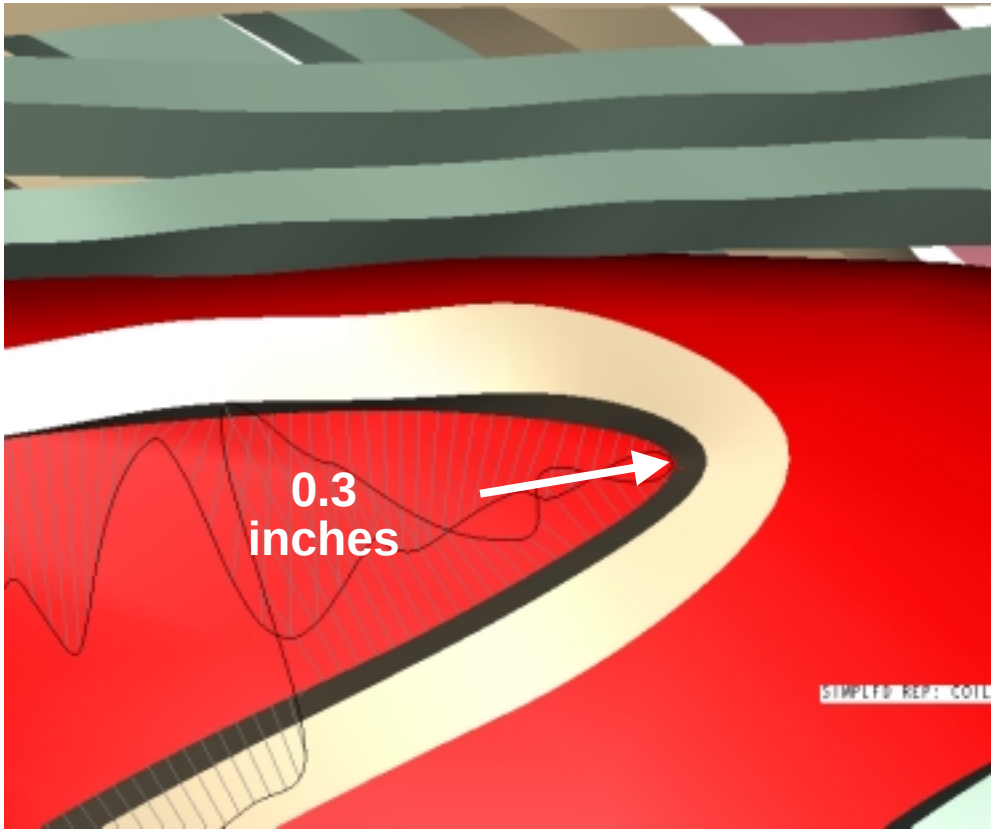
Cooling performance

- **Conductor cools in < 5 minutes to septum, if septum has efficient heat sink outside winding pack**



Bend radius

- **Saddle coils exhibit sharp radius at “turn-around” points**
- **Should be able to tweak shape**
- **Curve analysis shows very small radii**

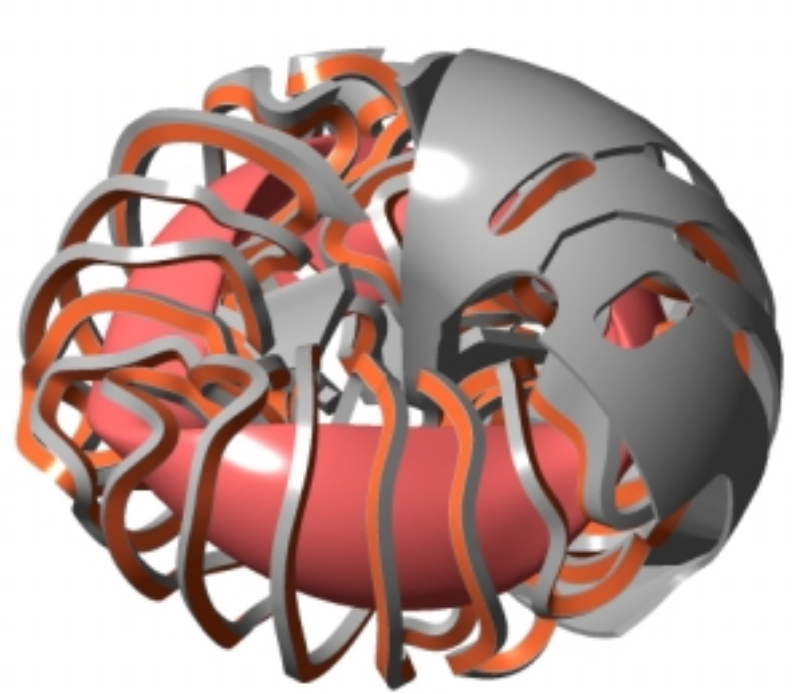


Saddle winding vs constraints

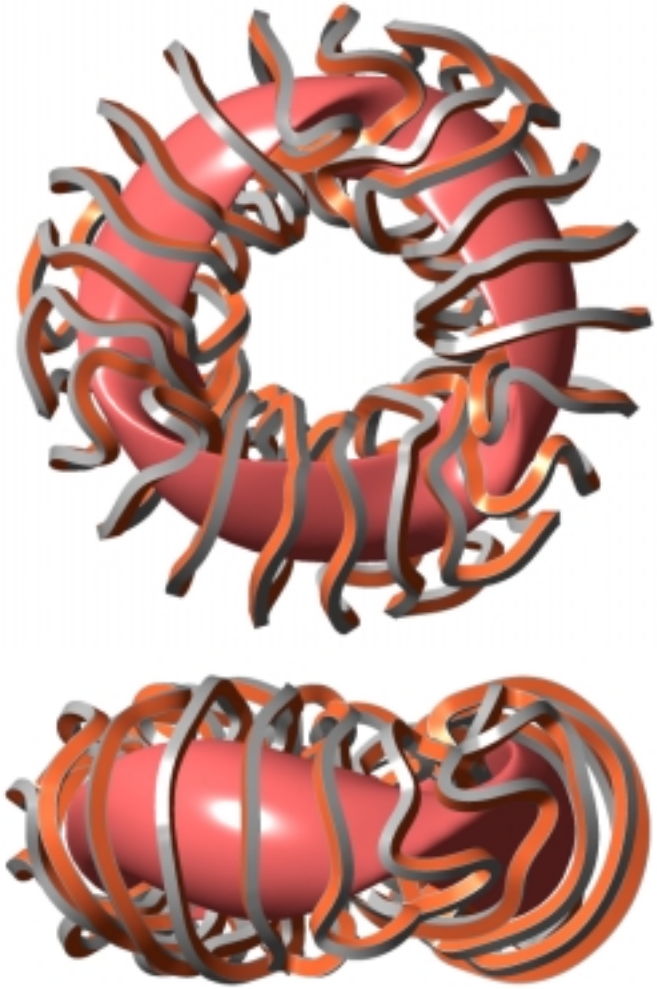
Parameter	Units	Design Limit	Present value	Margin
Max temp rise (assume T0 = 85K)	K	100	43	>100%
Min bend radius	mm	(3 x tcond)		
Coil 1		40	~45	~ 0
Coil 2		61	~28	< 0
Coil 3		47	~9	< 0
Coil 4		61	~10	< 0
Min slot width	mm	13	30	> 100%
Min ligament (at root)	mm	tbd	>11	tbd

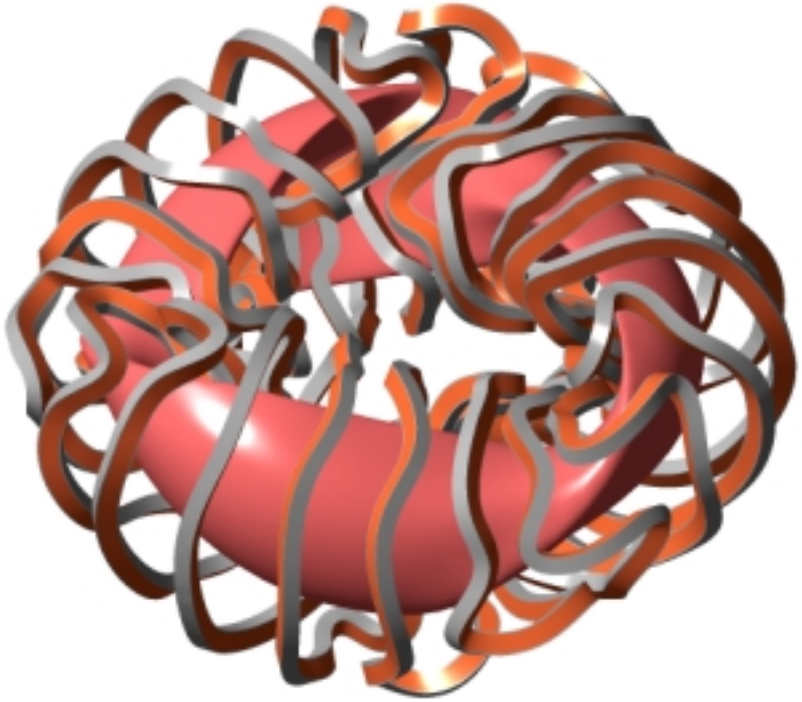
Modular Coil Option

- **Modular coil set li383-0907**
- **21 modular coils, 4 types**
- **1/R background field of +/- 0.2T**
- **7 pairs of PF coils**



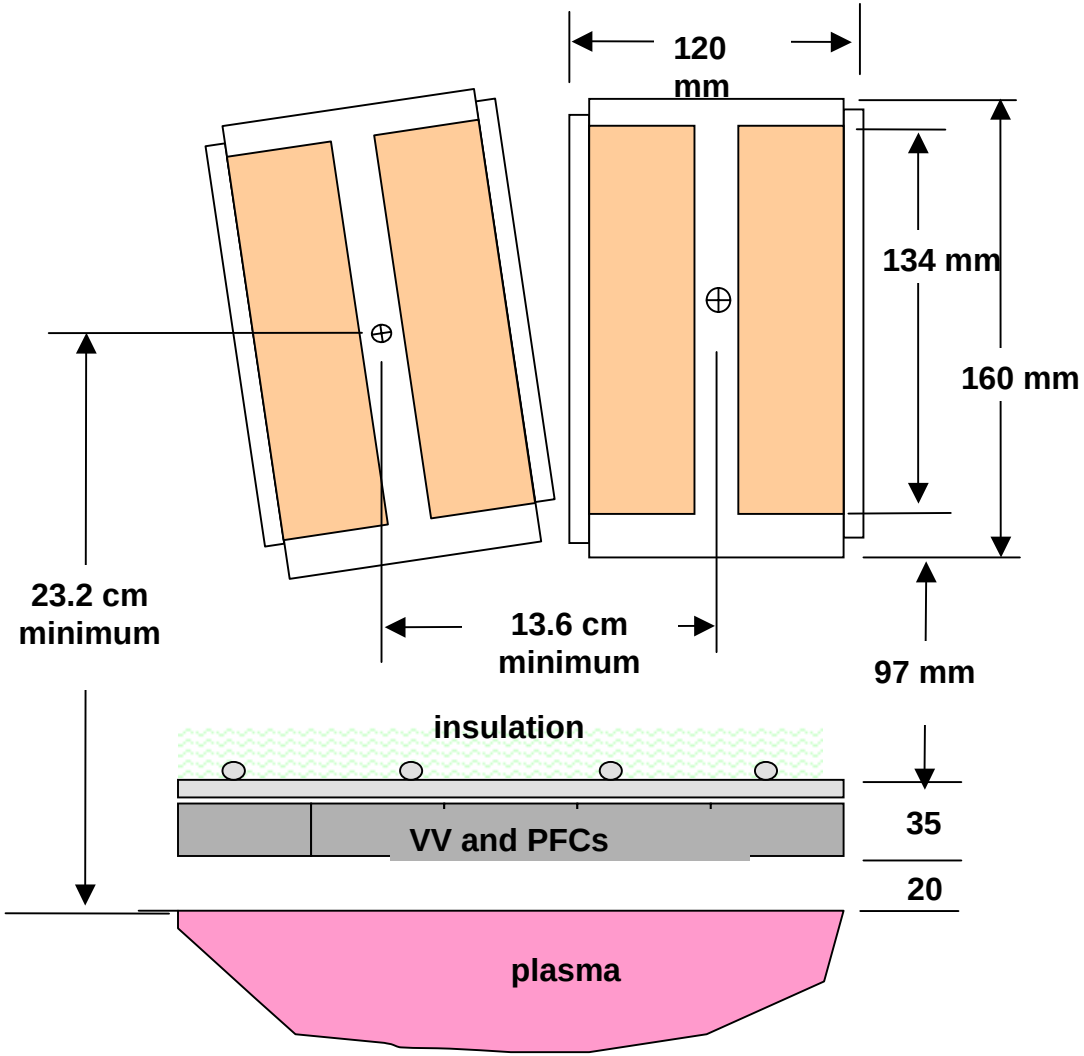
3 period modular coils



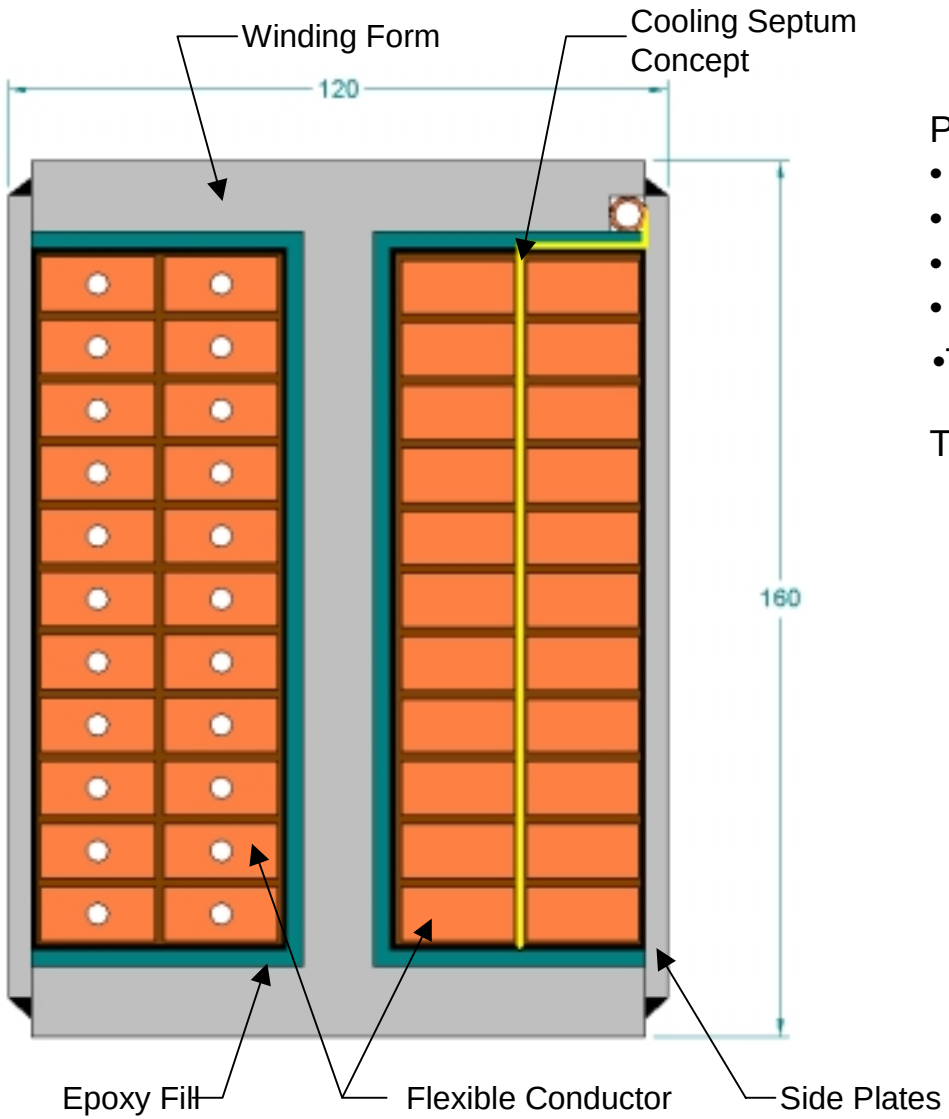


Nominal winding space

- **Relative twist of coils prevents full use of space**
- **Problem is local and tedious to fix**



Modular coil winding pack



Parameters:
- Coil Envelope = 12 x 16-cm
- Current / Coil = 864-kA @ 2-T
- Number of Turns = 44
- Current / Turn = 19.6-kA
- Total power = 427 MW

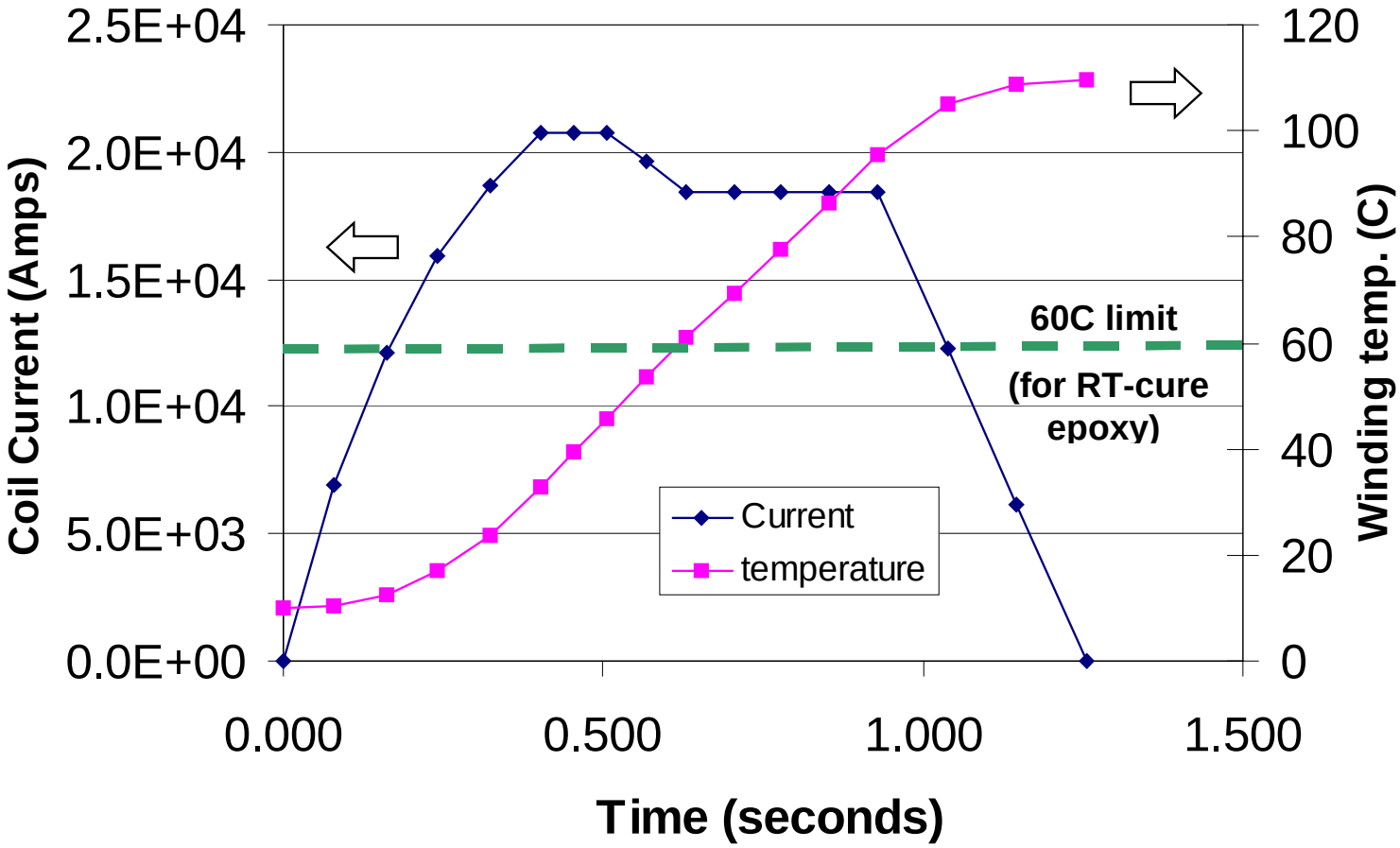
Two Winding Options:

Internal Passage:
- Conductor Size = 20.8 x 9.8-mm
- Hole Diameter = 4-mm
- Packing Factor = 75% (flexible cond)
- Net Current Density = 13.5-kA/cm2

Conduction to Septum:
- Conductor Size = 19.8 x 9.8-mm
- Septum Width = 2-mm
- Packing Factor = 75%
- Net Current Density = 13.4-kA/cm2

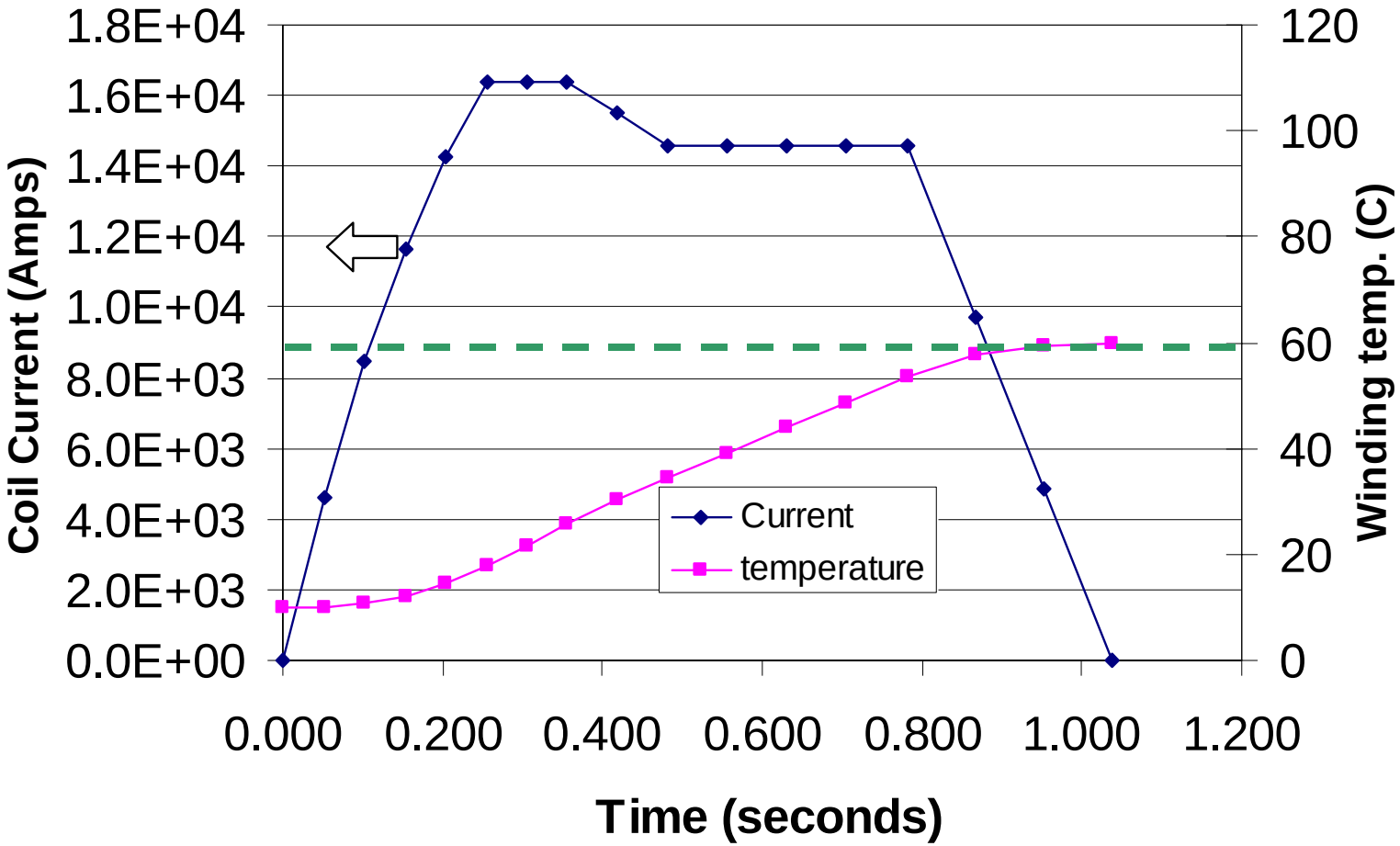
Temperature exceeds limit

- **Modular coils have high inductance, need modified pulse waveform**
- **1 kV per coil required for 0.4 second ramp**



Temp ok if J reduced 20%

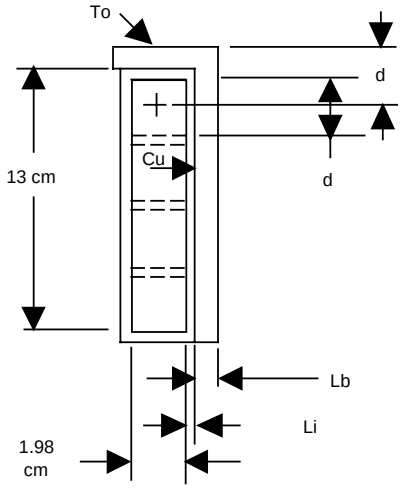
Cross section increased from 120x160 to 120x190 mm

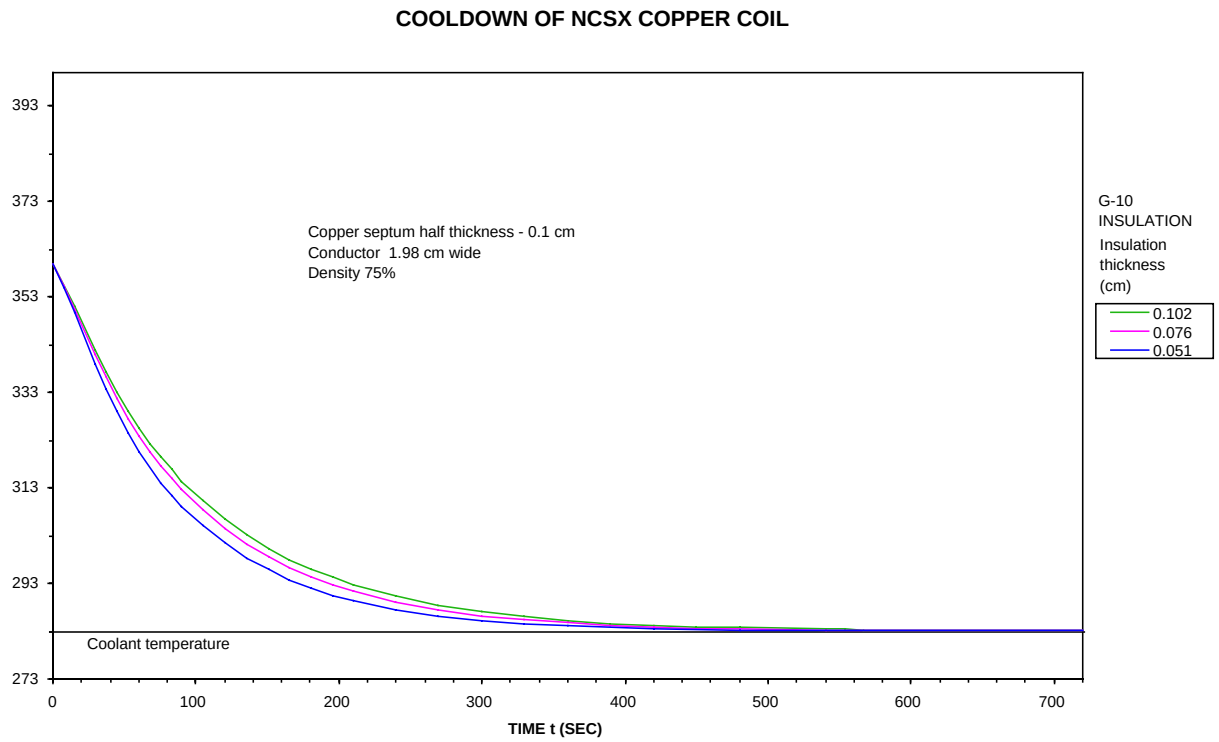


Modular coil cooling options

- **Gas cooling is preferred to avoid problems with water leaks, and to avoid extra thickness of water jackets on turns**
- **Internal cooling not practical for 22 x 7 m = 154 m cooling path (without multiple in-hand windings)**
- **Septum cooling appears to work with relatively modest gas flow cooling septum**
- **Alternate of flowing gas through septum space would only improve cooling**

Modular coil, septum cooling

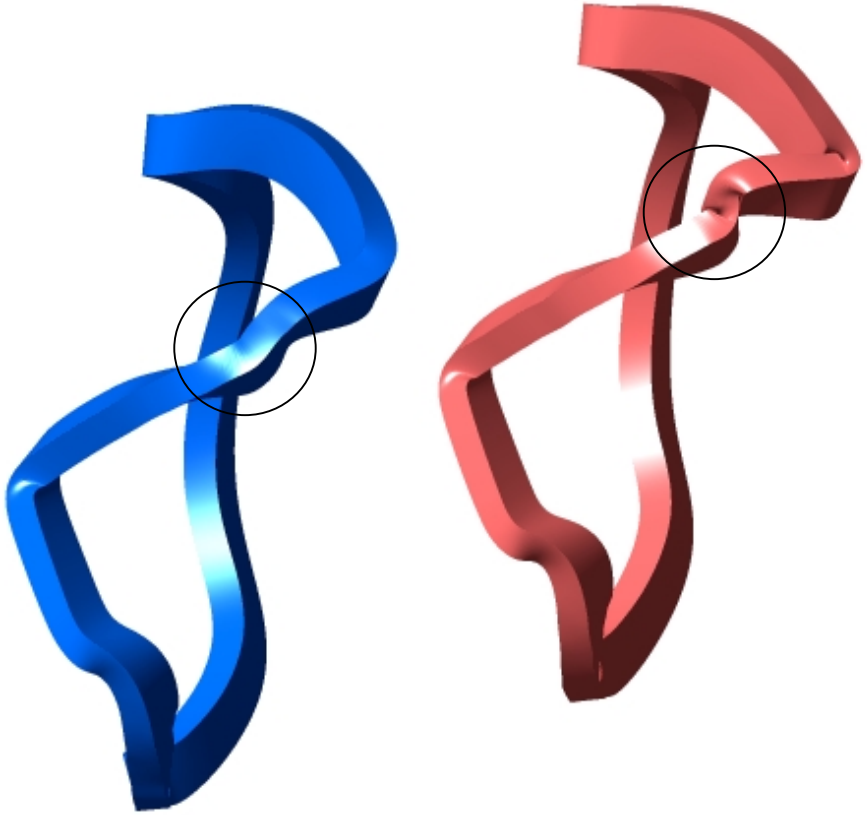




- **Conductor cools back to 10C in about 10 minutes**

Minimum bend radius

- **Bend radii should be on the order of 10 cm**
- **Initial coil cases only 4 cm, but optimization has produced ~9 cm minimum radius**
- **W7-AS and HSX coils have 11.5 and 8.1 cm minimum bend radii**
- **Twist has also been addressed, but more optimization needed**



Modular winding vs constraints

Parameter	Units	Limit	Design value	Margin
Max temp rise (assume T0 = 10C)	K	50 (RT epoxy) ~100 (HT epoxy)	92-108	< 0
Min bend radius*	mm	(3 x tcond)		
Coil 1		60	59.5	~ 0
Coil 2		60	29.5	< 0
Coil 3		60	65.5	~ 10%
Coil 4		60	91.5	~ 50%
Min web thickness	mm	tbd	13	tbd
Min flange thickness	mm	tbd	13	tbd

* Bend radius given to center of conductor nearest edge of pack

Summary

- **Windings compared for two candidate coil configurations, saddle and modular**
- **Saddle coils operate comfortably at 85-130K, 16 kA/cm^2**
- **Modular coils push the limits at 10-110C, 13.5 kA/cm^2**
- **Conduction cooling to septum appears to work for both coil types**
- **Both windings need geometry tweaks to optimize twist and keep bend radius in limits**