Magnet requirements and limitations

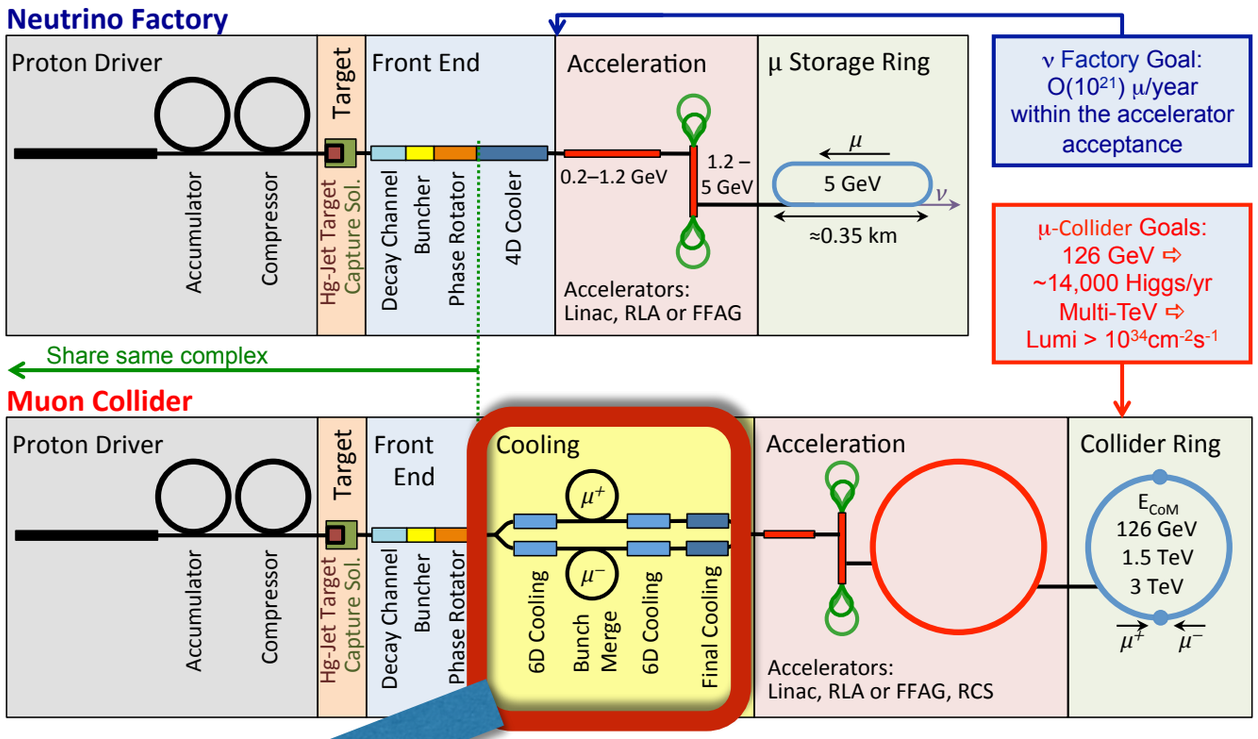
Soren Prestemon
Lawrence Berkeley National Laboratory

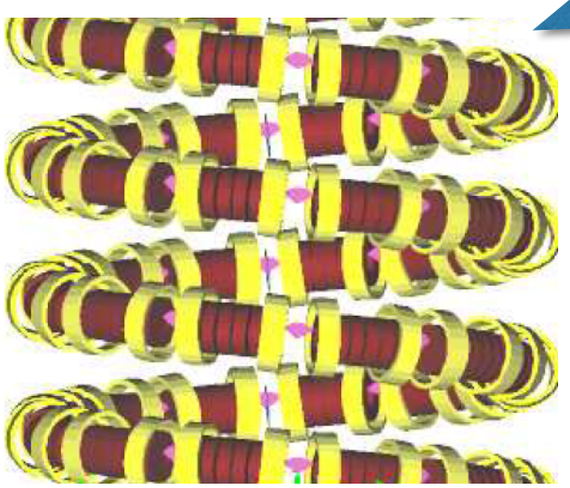
Outline

- Vacuum cooling channel concept
- Magnet design requirements
- Assumptions for conceptual design
- First design layout:
  - ➡ Magnetic performance and issues
  - ➡ Mechanical performance and issues
- Summary

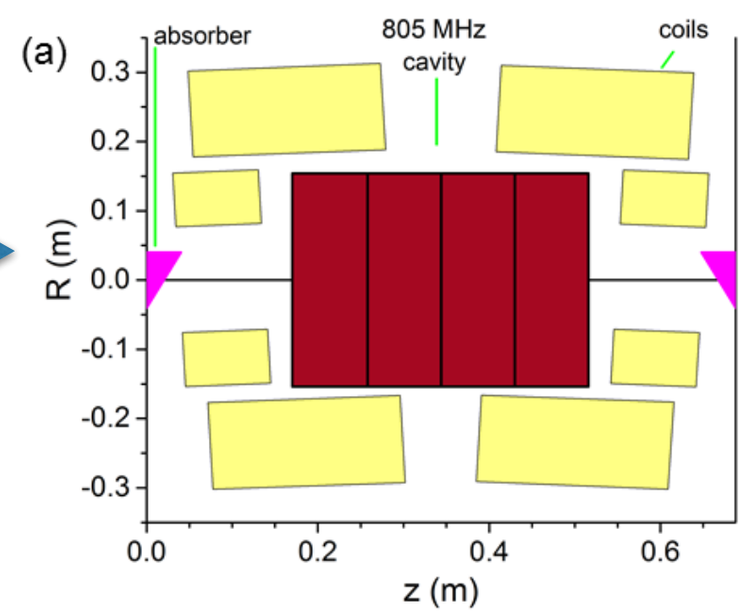
Special thanks to
Holger Witte (BNL) and ***Frank Borgnolutti (LBNL)***
who performed the analyses presented here

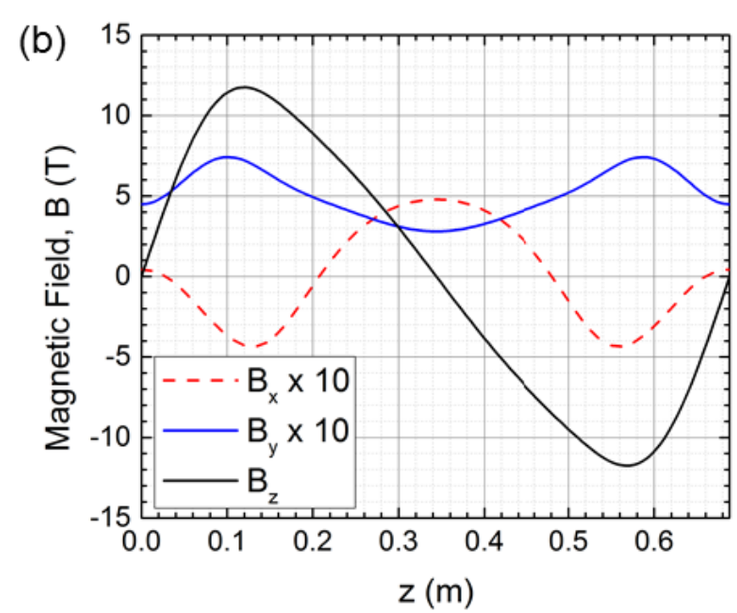
Cooling channel magnets



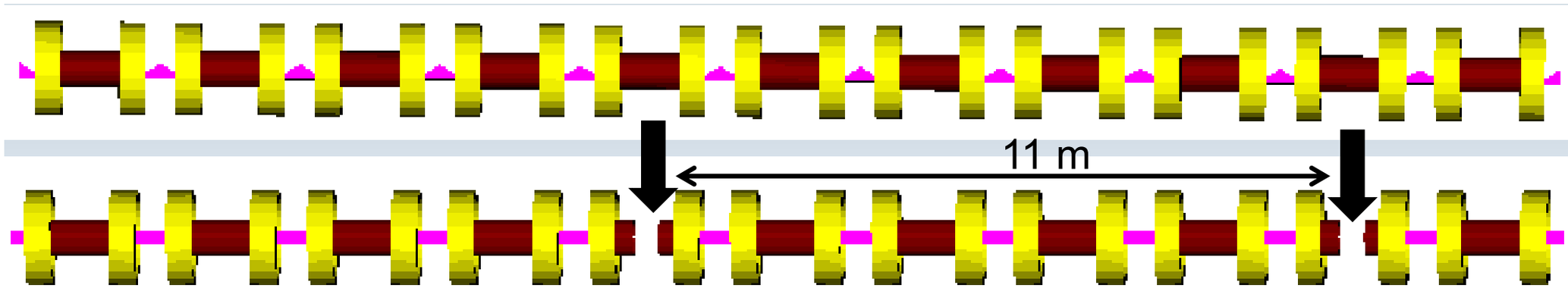


"Guggenhiem"

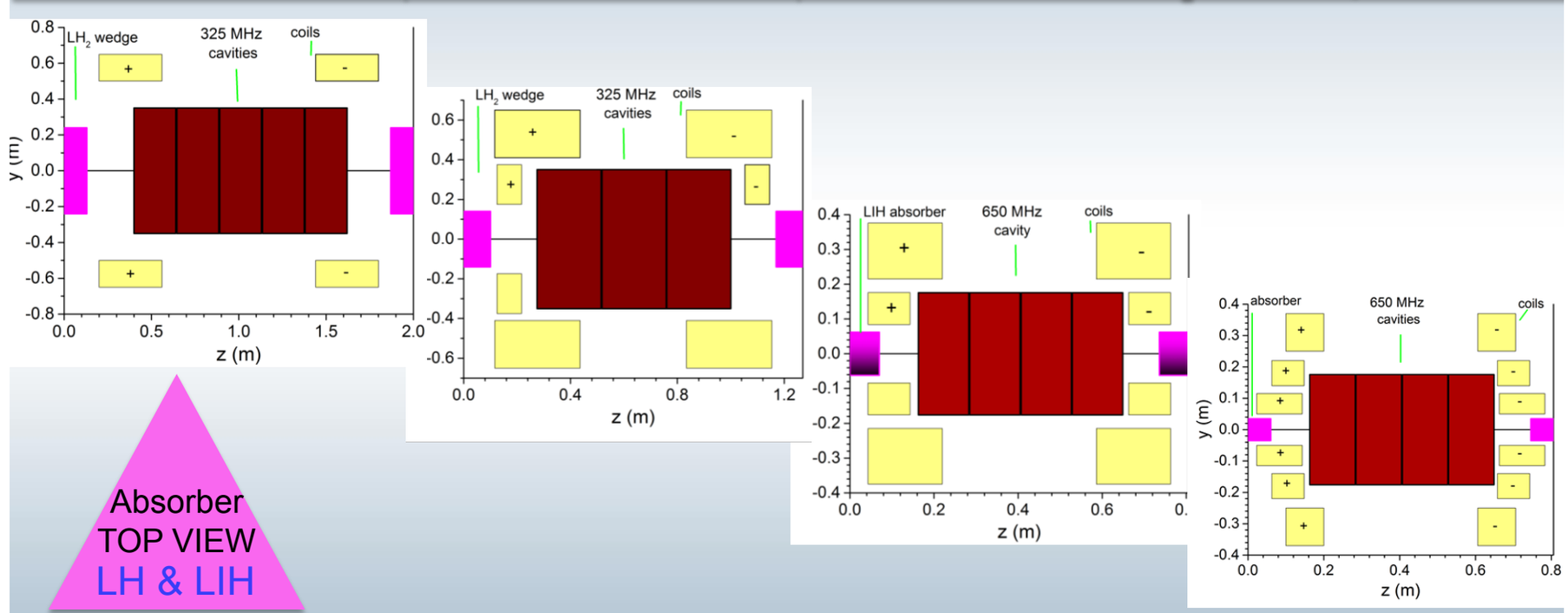




Layout (from D. Stratakis)



STAGE 2	STAGE 4	STAGE 6	STAGE 8
64 m (32 cells)	62.5 m (50 cells)	62 m (77 cells)	41.1 m (51 cells)



Absorber
TOP VIEW
LH & LIH

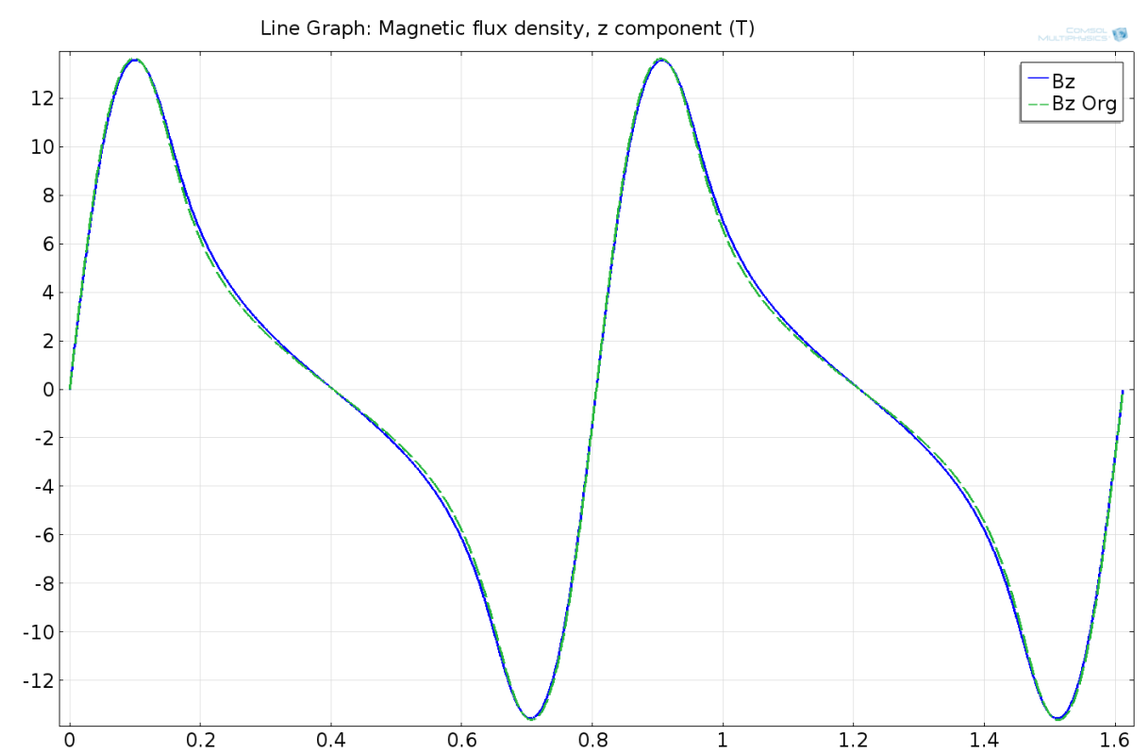
3.7 T (8.4 T)	6.0 T (9.2 T)	10.8 T (14.2 T)	13.6 T (15.0 T)

Magnet design requirements

- Specific field profile to satisfy requirements for transverse cooling and longitudinal-transverse emittance exchange

- Design must be "realizable":
  - ➡ Realistic coil cross-sections
  - ➡ Realistic support structures
  - ➡ Available materials (properties)
  - ➡ Basic assembly feasibility

Recent
***Vacuum Cooling Channel Workshop**,*
held at LBNL, helped clarify some outstanding interface and space requirements issues



Assumptions for conceptual design

- Magnetics:
  - ➡ Use superconductor properties that are commercially available
  - ➡ Assume coil J_E that is demonstrated to be feasible

- Mechanical:
  - ➡ Structures use readily available and proven materials
  - ➡ Apply realistic boundary conditions (stick-slip, pre-stress)
  - ➡ Some space allocated for cryogenics

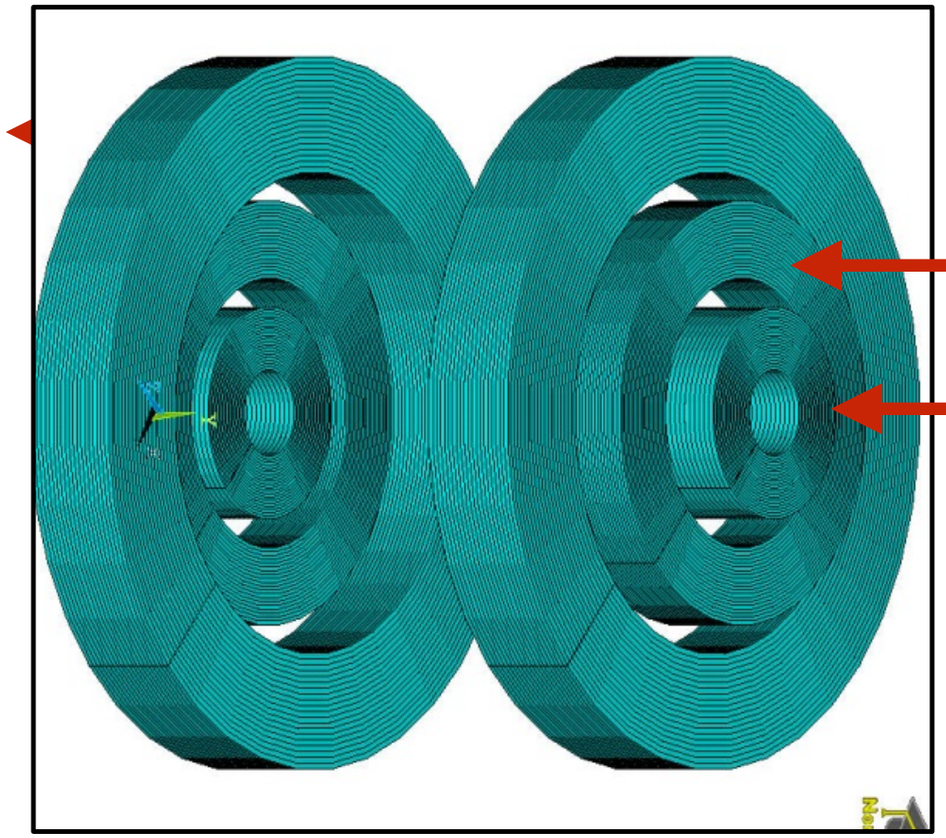
First layout: overview

- Consider "tilted" and "straight" solenoids
- Fill factors based on sampling of existing magnets
- Properties from commercially available superconductors

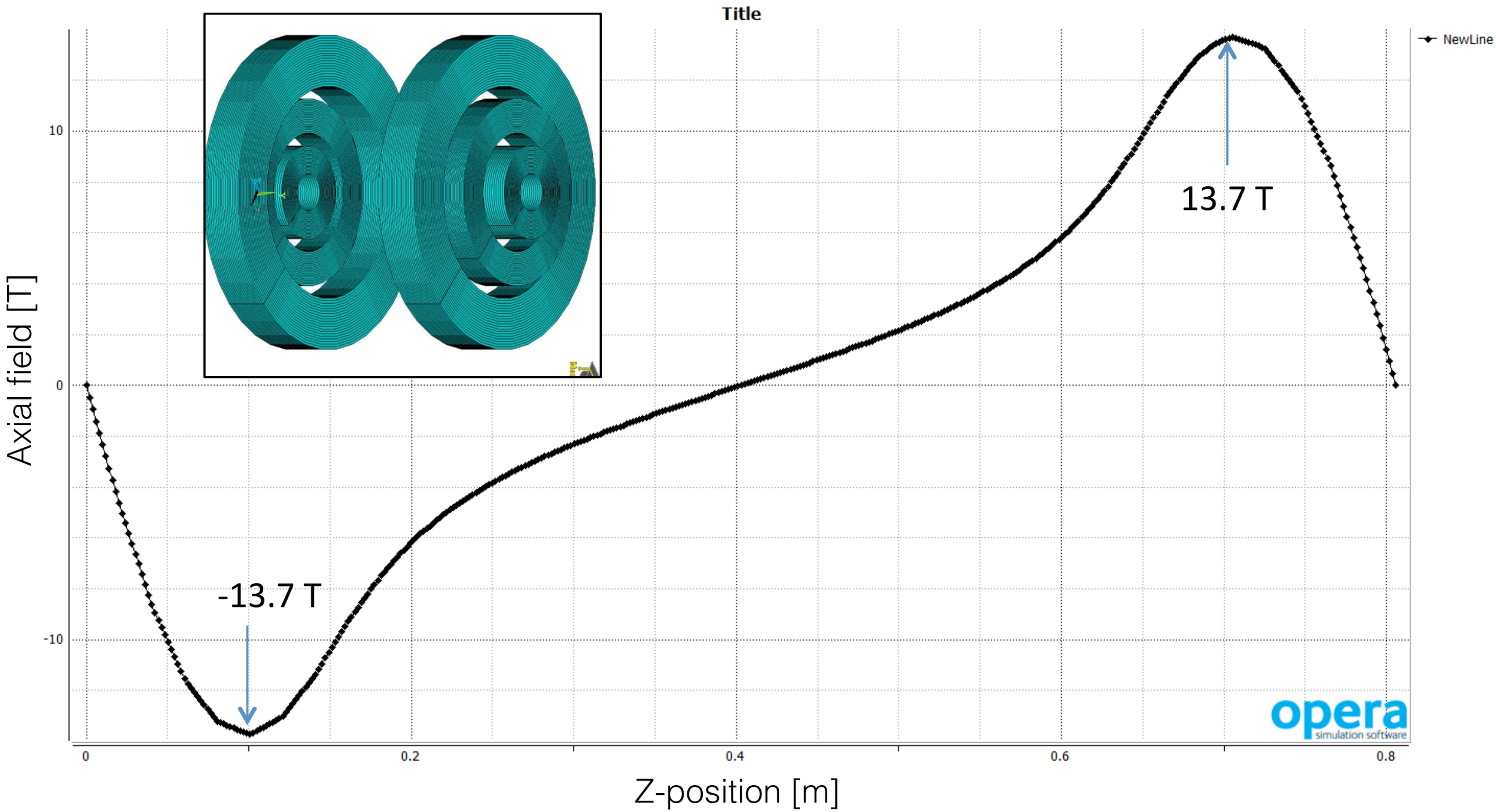
$$J_E = kJ_{SC}$$

Material	Magnet	*k*	average
	Tevatron MB	0.23	
	HERA MB	0.26	
	SSC MB inner	0.30	
	SSC MB outer	0.27	
Nb-Ti	RHIC MB	0.23	**0.26**
	LHC MB inner	0.29	
	LHC MB outer	0.24	
	FRESCA inner	0.29	
	FRESCA outer	0.26	
	CERN-Elin inner	0.29	
	CERN-Elin inner	0.26	
	MSUT inner	0.33	
	MSUT outer	0.34	
Nb3Sn	LBNL D20 inner	0.48	**0.33**
	LBNL D20 outer	0.34	
	FNAL HFDA02-03	0.29	
	NED	0.31	
Nb3Sn	HQ quadrupole	0.32	0.32
Nb3Sn	HD2	0.33	0.33

Reference: L. Rossi and Ezio Todesco, «**Electromagnetic design of superconducting dipoles based on sector coils"**, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **10**, 112401 (2007)

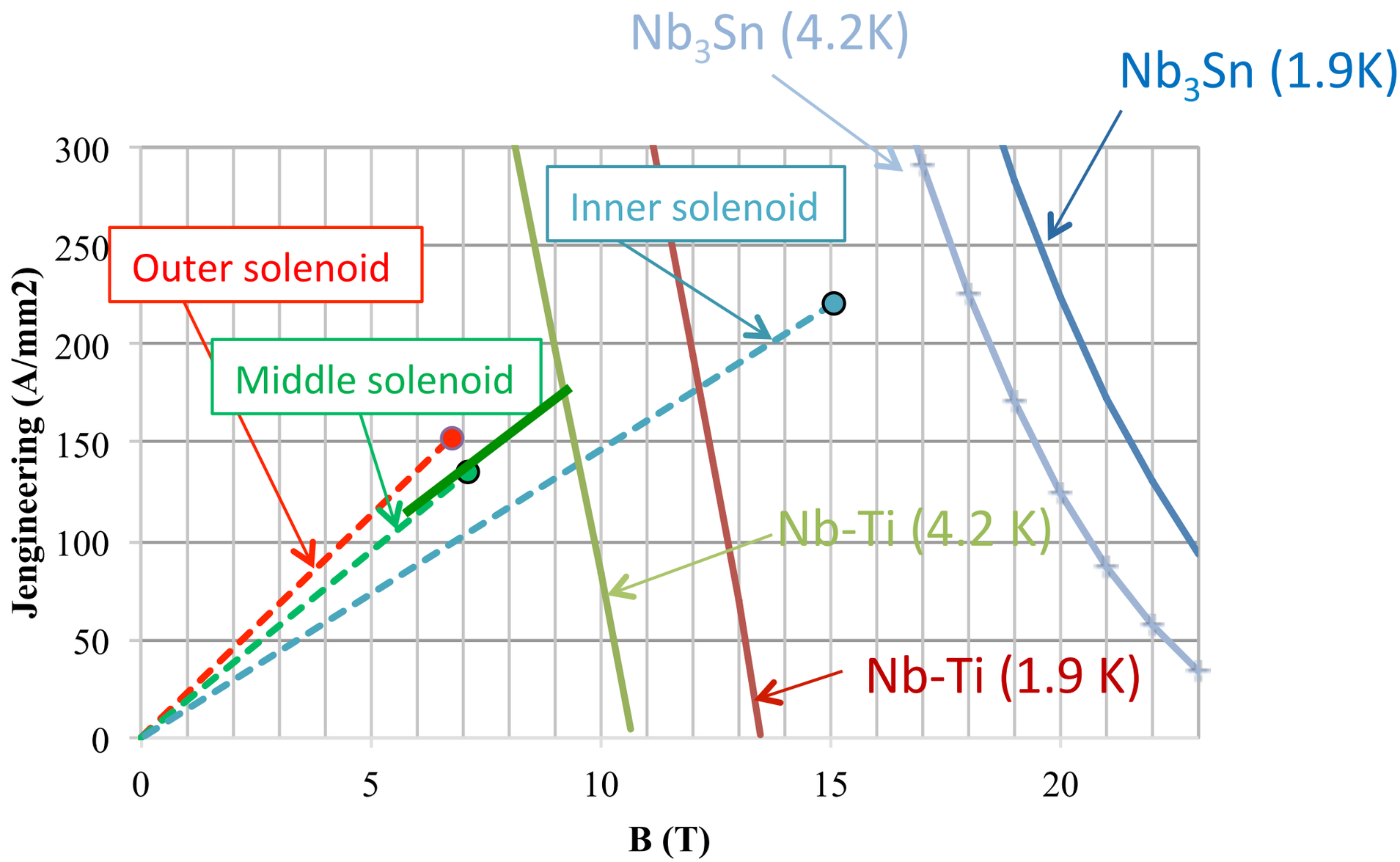


Axial field profile



Magnetics: load lines

- Assume OST RRP Nb_3Sn (Godeke fit; 5% degradation, SF-corrected)
- Assume NbTi with 3kA/mm^2 @ 5T, 4.2K (Bottura fit)



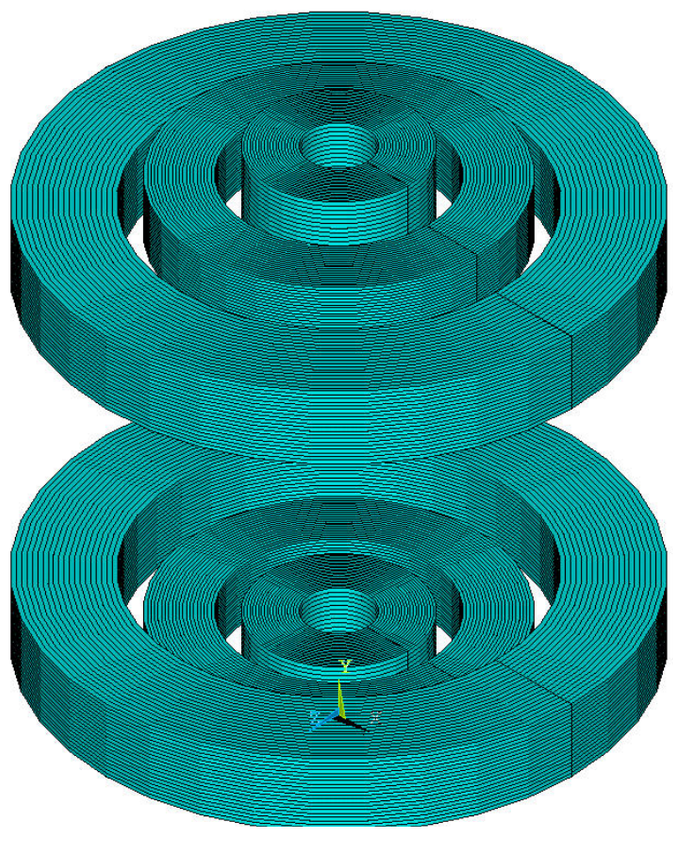
Magnetics - status

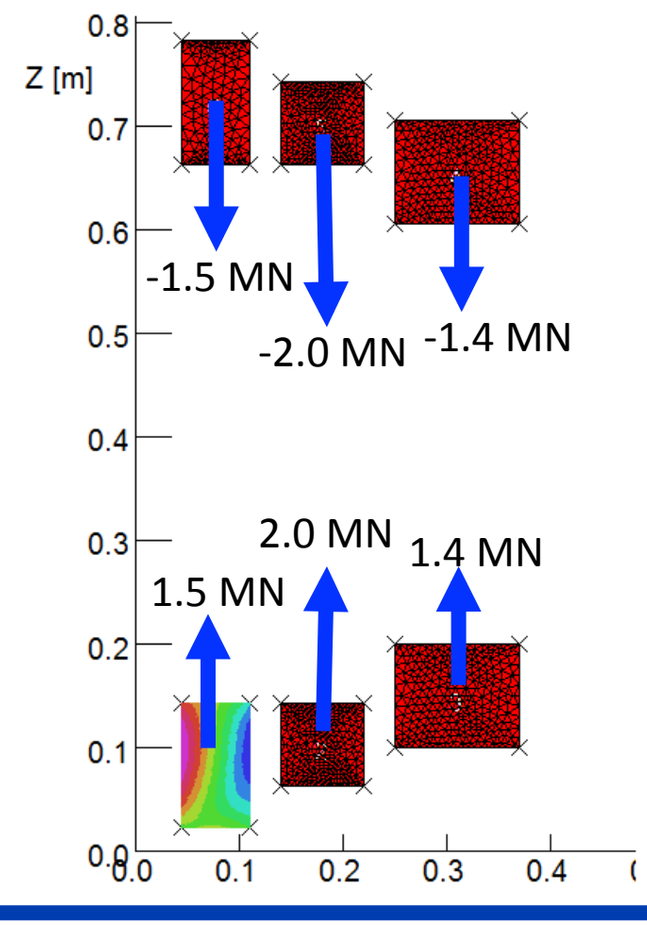
- Middle and outer (NbTi) coils have ample margin
- Inner (Nb_3Sn) solenoid is marginally feasible
  - ➡ room for further optimization (iteration with beam modeling)
- Both single-wire and Rutherford cable can be considered
  - ➡ Magnet protection: inductance considerations (not yet addressed)
    - ✓ know that solutions exist (prefer passive, but may need active)
  - ➡ dB/dt-induced quenching down the train needs to be evaluated
    - ✓ mitigate by judicious grouping, possible eddy-current field clamping

	% of the load line at operational current		
	Inner solenoid	Middle solenoid	Outer solenoid
Nb-Ti @ 4.2 K	-	76%	74%
Nb-Ti @ 1.9 K	-	59%	58%
Nb3Sn @ 4.2 K	88%	-	-
Nb3Sn @ 1.9 K	81%	-	-

Structure: magnetic forces

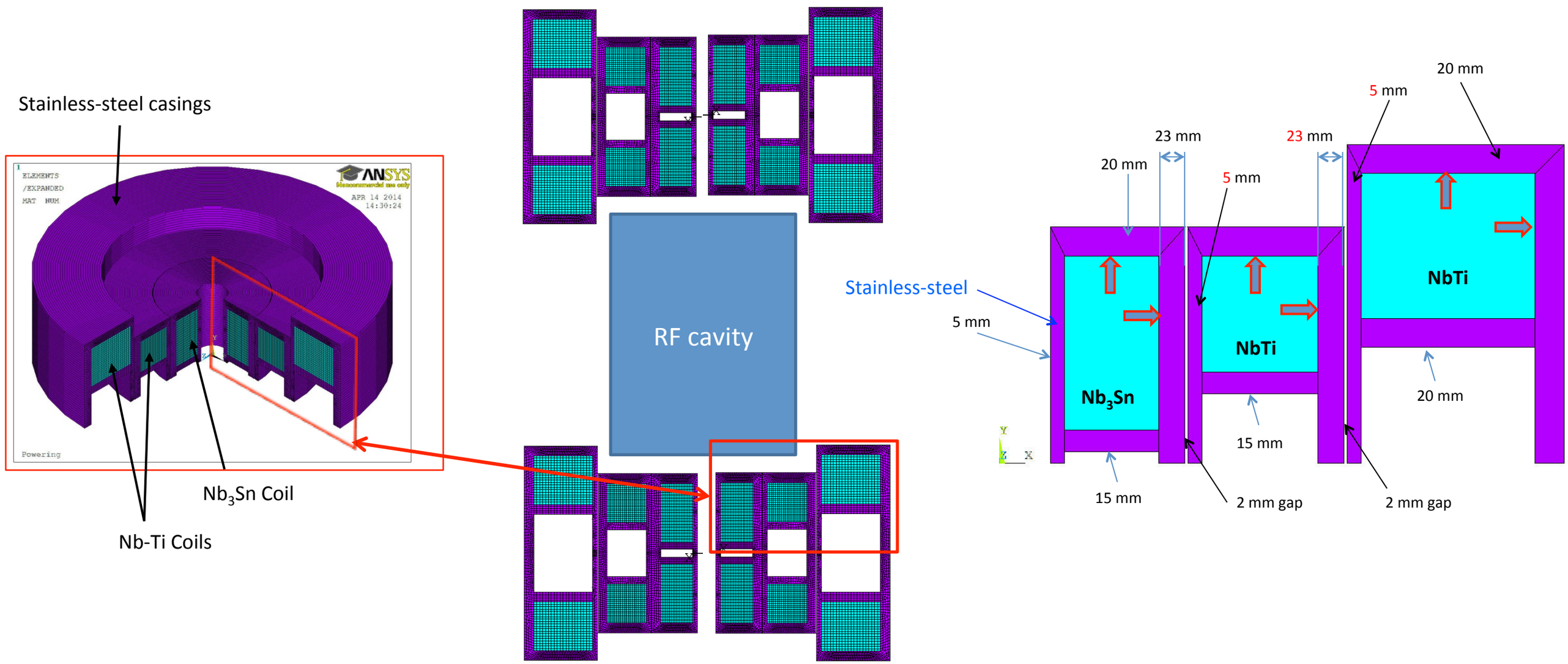
- Significant longitudinal forces between coils
  - ➡ No fault-force analysis so far
- Prefer groupings with zero net longitudinal force
  - ➡ but recognize inter-grouping forces will arise if one quenches





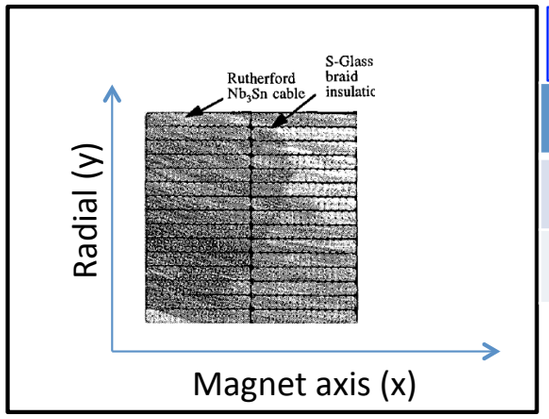
Conceptual layout

- Sliding without friction for all coil/structure contact surfaces
- Separation allowed



Coilpack properties

- Use historical data from various magnet types



From 295 to 77 K			
	X (m/m)	Y (m/m)	Z (m/m)
Nb-Ti	-0.00341	-0.00437	-0.00274
Nb_3Sn	-0.00305	-0.00367	-0.00305

References:

- **M. Reytier** et al., "Characterization of the thermo-mechanical behaviour of insulated cable stacks representative of accelerator magnet coils (2001).
- **D. R. Chichili** et al., "Investigation of cable insulation and thermo-mechanical properties of epoxy impregnated Nb_3Sn composite" (2000).
- **Ken P. Chow** et al., "Measurements of modulus of elasticity and thermal contraction of epoxy impregnated Niobium-Tin and Niobium-Titanium composites (1999).
- **Iain R. Dixon** et al., "Mechanical properties of epoxy Impregnated Superconducting solenoids" (1996).

	Reference	Year	Insulation	Cond	Loading	Direction X (Gpa)	Direction Y (Gpa)	Direction Z (Gpa)
Nb-Ti	Dixon	1996	DGEBA resin + E-glass cloth	rect strand	1 cycle	59.3	41.0	99.5
	Chow	1998	Epoxy + glass cloth	rect strand	Monotonic	52.9	44.4	56.8
	Chow	1998	Mixture law	rect strand		35.3	35.3	106.2
	Reytier	2001	epoxy + 60µm quartz fiber tape	cable	Cyclic	-	46	-
Nb_3Sn	Chow	1998	Epoxy + Sglass braid	cable	Monotonic	34.5	27.6	67.7
	Chow	1998	Mixture law	cable		34.4	24.6	80.6
	Reytier	2001	epoxy + 60µm quartz fiber tape	cable	Cyclic	-	45	-
	Chichili	2000	epoxy CTD-101K + S2 glass	cable	Monotonic	-	26	56
	Chichili	2000	epoxy CTD-101K + S2 glass	cable	Cyclic	-	40	-

Material	E, GPa		Poisson's Ratio
	300 K	4.2 K	
Nb_3Sn + S-2	39	40	ν_{12}= 0.15; ν_{32}= 0.34
Nb_3Sn+ceramic	38	38	ν_{12}= 0.14; ν_{32}= 0.33

Table 4: *Azimuthal modulus and Poisson's ratio of the composite after massaging to 100 MPa.*

D.R. Chichili et al., Investigation of Cable Insulation and Thermo- Mechanical Properties of Nb3Sn Composite.

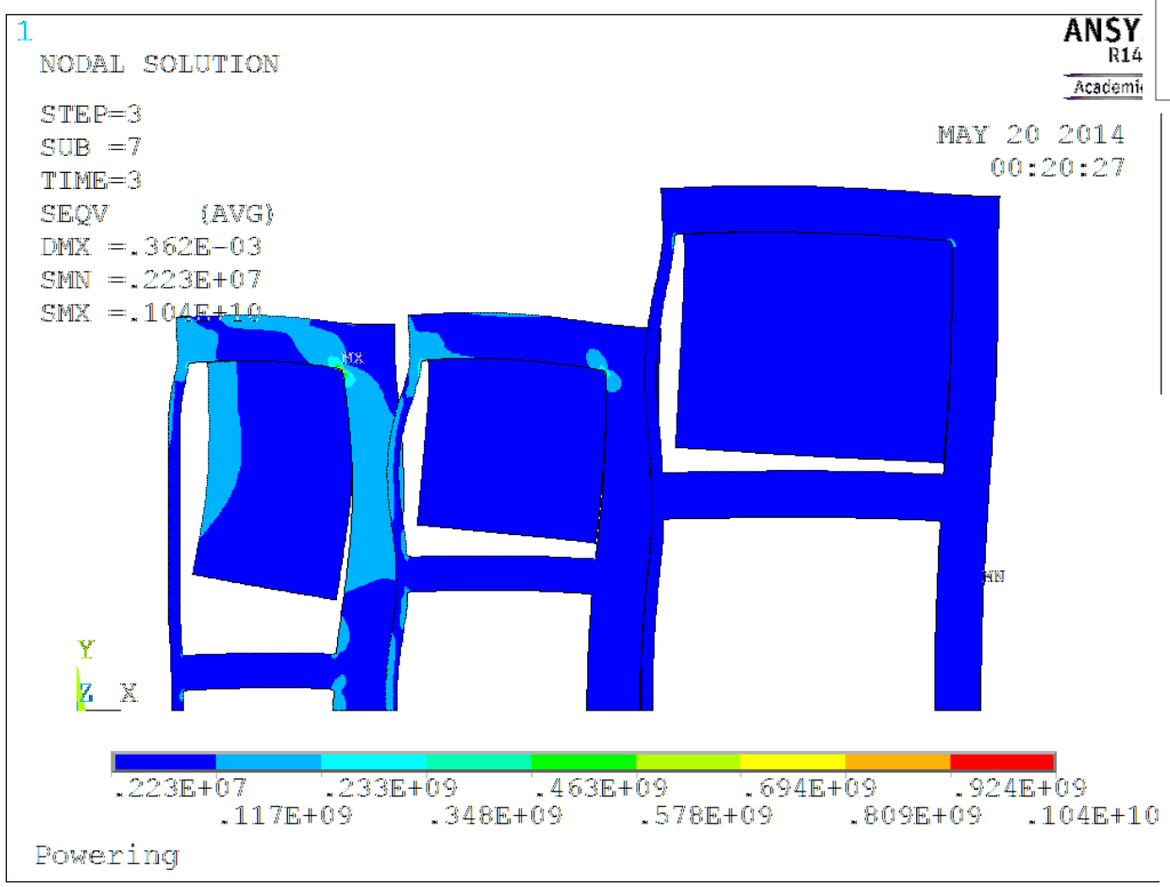
TABLE II
TENSILE PROPERTIES OF NbTi COIL COMPOSITES AT 77 K AND 4.2 K

Specimen	Temp. (K)	Load Direction	Young's Modulus (GPa)	ν_{12}	ν_{13}
1	77	1	96	0.345	0.428
1	4.2	1	99	0.402	0.445
2	77	1	94	0.316	0.377
2	4.2	1	100	0.379	0.403
Average	77	1	95.0	0.331	0.403
Average	4.2	1	99.5	0.391	0.424

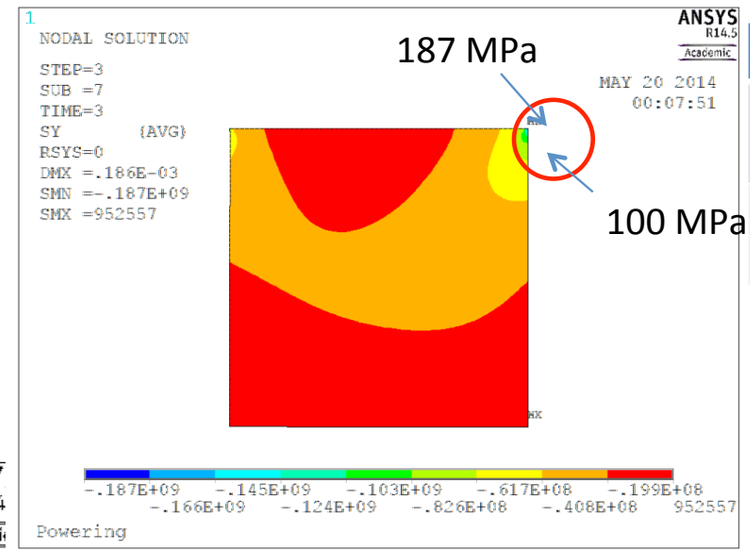
I. Dixon et al. Mechanical properties of epoxy impregnated superconducting solenoids

Structural analysis: version 1

- Version 1: no pre-stress
- Evaluate states at:
  - ➡ cooldown
  - ➡ Energized



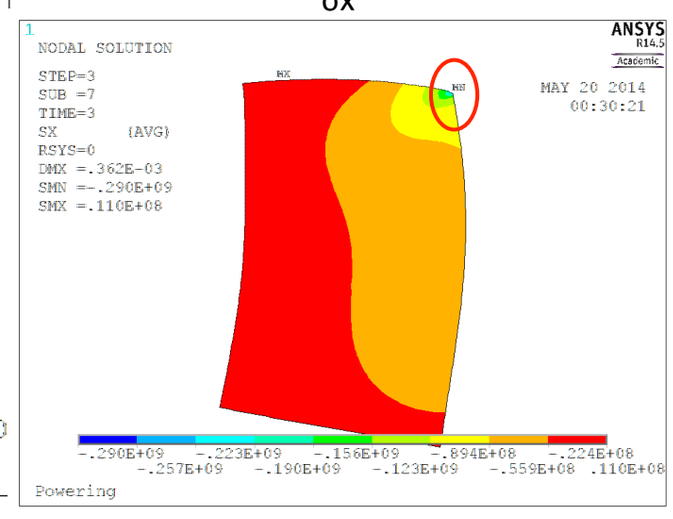
NbTi



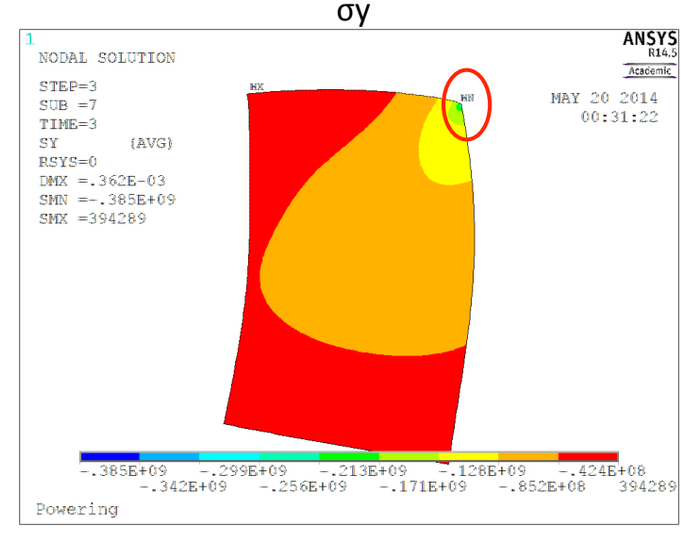
	σx (MPa)	σy (MPa)	σz (MPa)
Middle solenoid	150	187	200
Outer solenoid	53	70	68

Nb_3Sn

σx



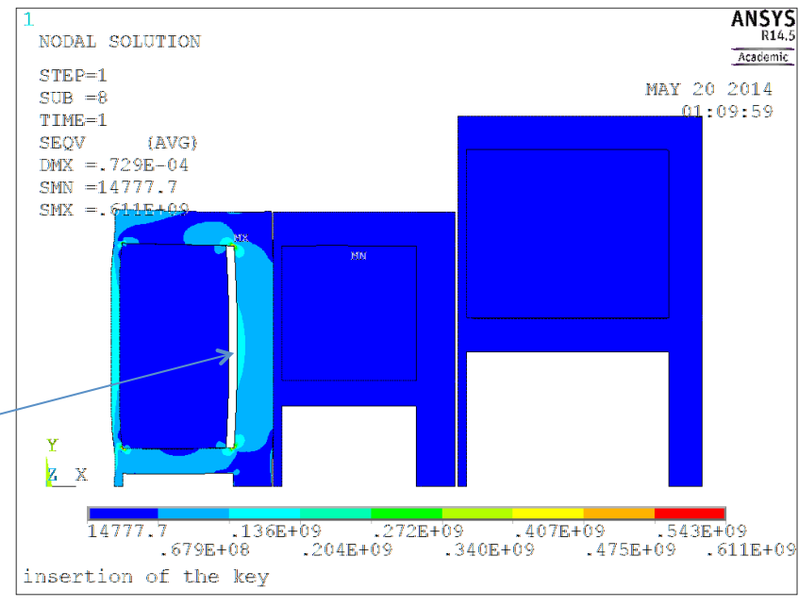
σy



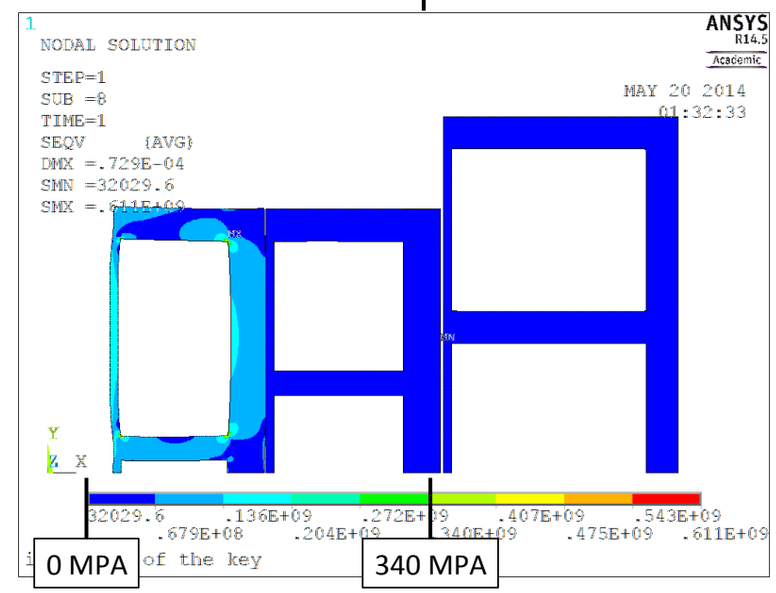
Structural analysis: version II

- Version II: pre-stress
- Evaluate states at:
  - ➡ assembly
  - ➡ cooldown
  - ➡ Energized

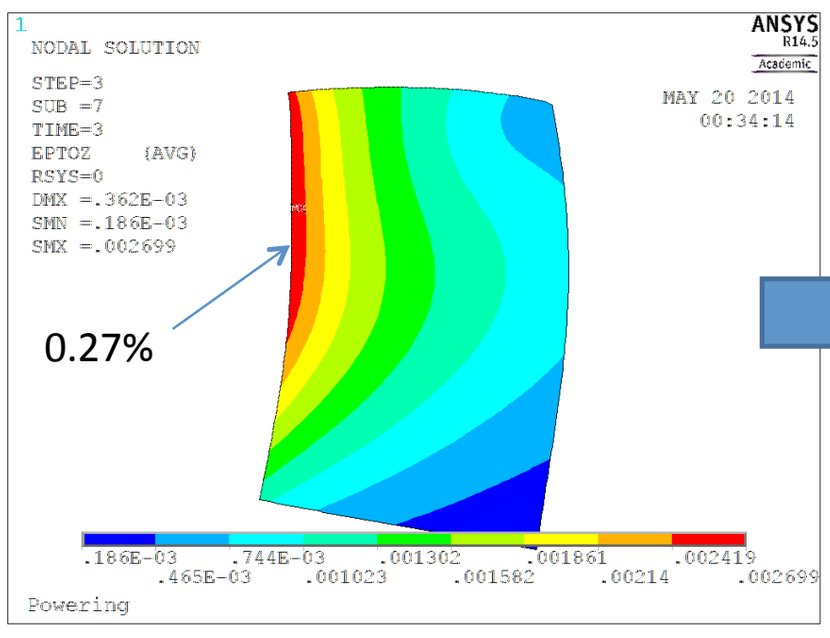
100 µm shim



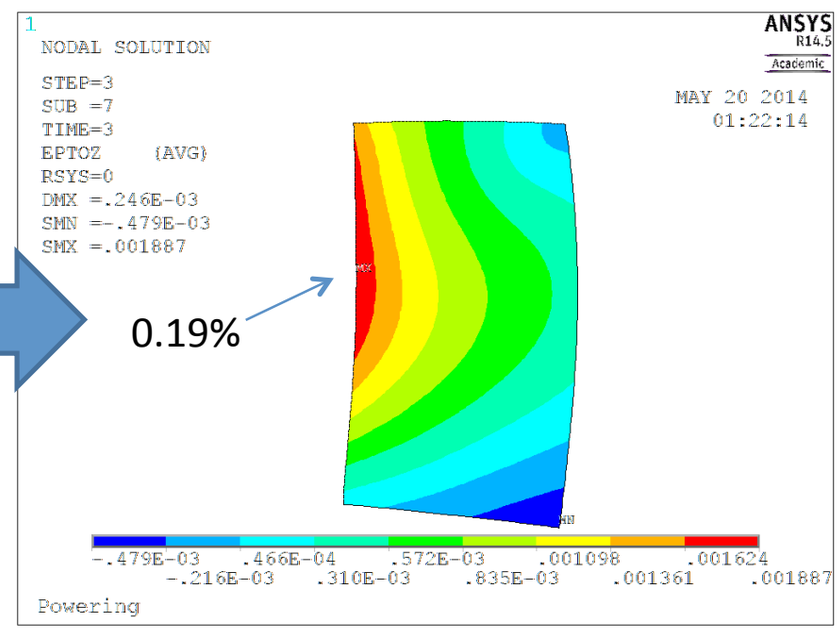
Room temperature



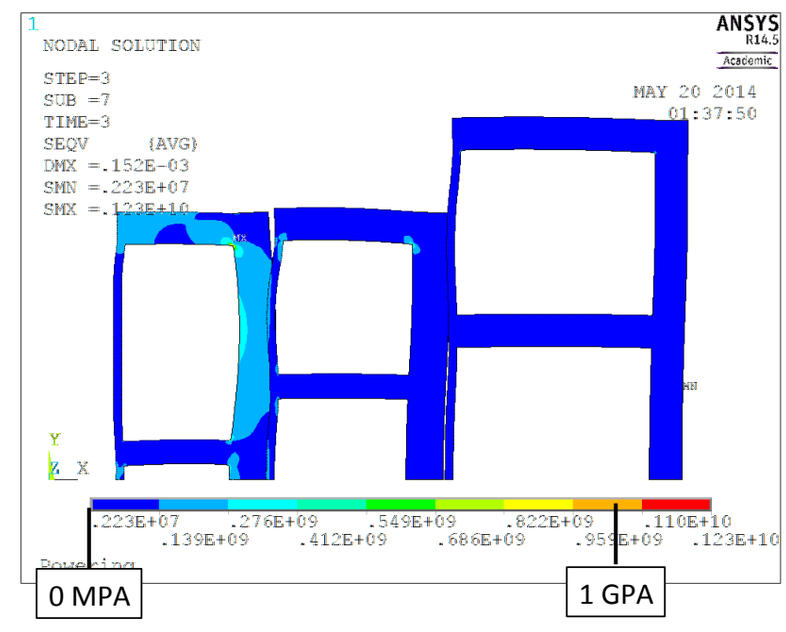
No radial shim



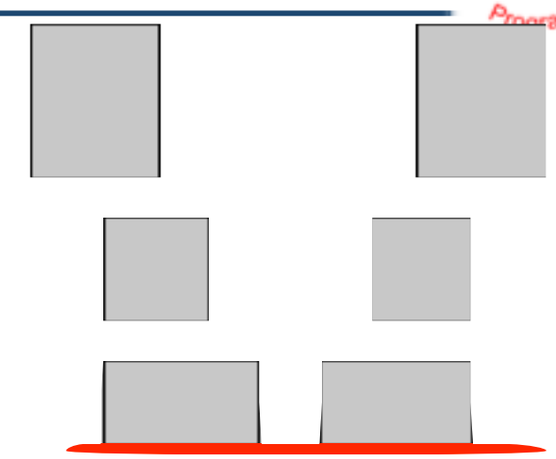
With 100 µm radial shim



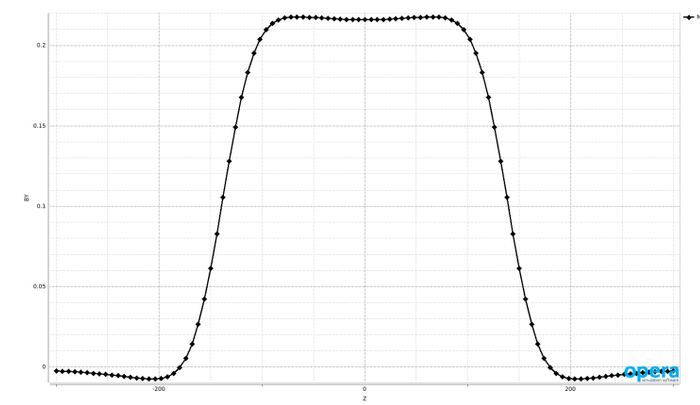
Cold+Energized



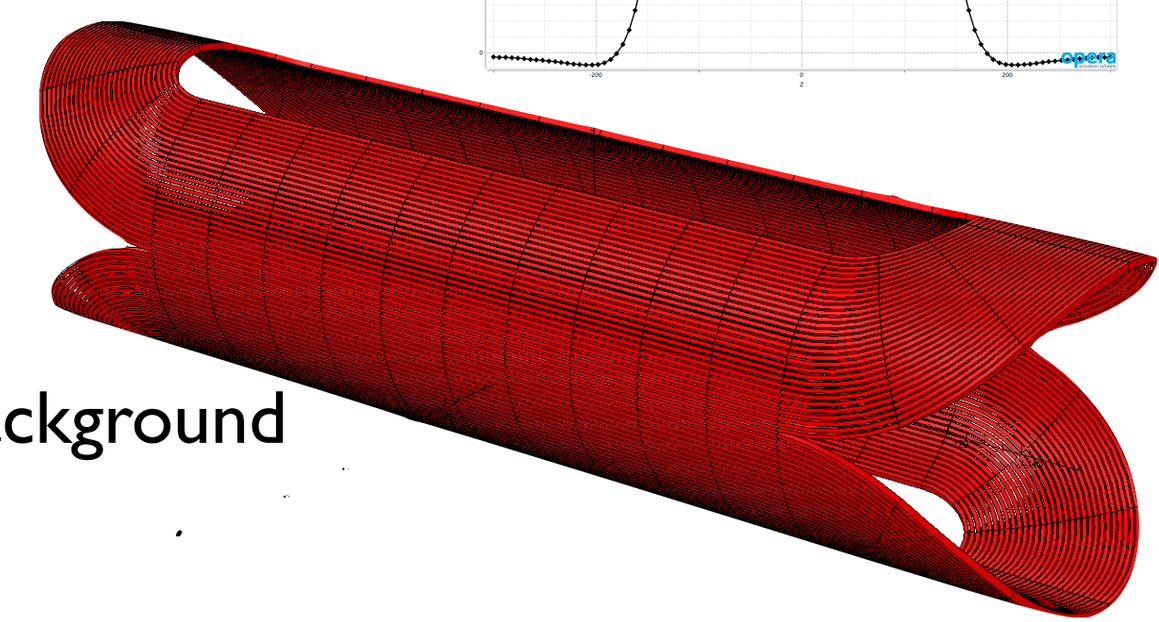
Tilting vs dipole superposition



- Tilting:
  - ➡ "benign" tilt angle
  - ➡ may need additional "knob"



- Dipole superposition:
  - ➡ clean "knob"
  - ➡ solenoids keep rotational symmetry
  - ➡ need space for dipole
  - ➡ dipole sees high field (~1T on 15T background



Summary

- First conceptual design of the vacuum cooling channel magnets
  - ➡ Basic feasibility being established (pending optimization)
  - ➡ Need to clarify and document requirements for cryogenics and vac. RF
    - ✓ Vacuum Cooling Workshop helped significantly
  - ➡ Room for improvement:
    - ✓ Iterate magnet design and beam modeling to better optimize performance versus magnet complexity/risk
    - ✓ Use magnet modeling tools to iterate/optimize design:
      - materials selection
      - develop pre-stress concept
- No show-stoppers, but…
  - ➡ lots to do: magnet protection, powering, fault scenarios, …

Most importantly, a design <u>process</u> and design <u>tools</u> are being developed to allow iterative analysis