Design and development of conduction cooled MgB_2 magnets for 1.5 and 3.0T full body MRI systems

EUCAS 2017

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Most recent papers on MRI applications using MgB_2:

- ***T. Baig,* SuST *27 (2014) 125012*** "Conduction cooled magnet design for 1.5 T, 3.0 T and 7.0 T MRI systems"
- ***C. Poole,* SuST *29 (2016) 44003*** "Numerical study on the quench propagation in a 1.5 T MgB_2 MRI magnet design with varied wire compositions"
- ***A. Amin,* SuST *29 (2016) 55008*** "A multiscale and multiphysics model of strain development in a 1.5 T MRI magnet designed with 36 filament composite MgB_2 superconducting wire"
- ***T. Baig,* SuST *30 (2017) 043002*** "Conceptual Designs of Conduction Cooled MgB_2 Magnets for 1.5 and 3.0 Tesla Full Body MRI Systems"

Supporting Agencies:

NIH
State of Ohio
DOE
NASA

Outline

⌘ 1.5 and 3.0 T MgB_2 MRI

- Magnet criteria and design choices
- Magnetic design
  - Wire choice
- Conduction cooling
- Mechanical and thermal design
- Quench protection
- Persistent joints and switch
- Design evaluation tests
  - Test coil

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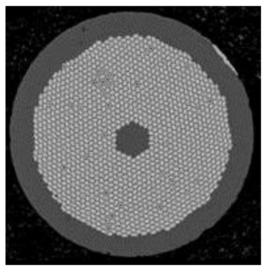
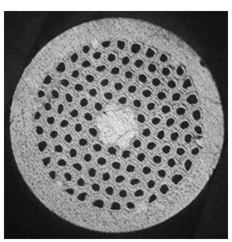
Superconductivity Industry Experience

Experience in conductor manufacturing, coil fabrication or both:

- BSCCO
- MgB_2
- Nb_3Al
- Nb_3Sn
- NbTi
- Pnictides
- YBCO
- Other non-ferrous non-superconducting





Processing equipment:

- Wire drawing equipment and furnaces for R & D conductor development
- Welded seam CTFF process for mono and multi-filament wire (one shift 10,000 km/yr capacity)
- Large capacity twisting
- Wire-in-channel soldering
- Insulation braiding
- Coil winding capacity designed for strain-sensitive wire

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Magnet criteria and design choices

- 60 cm warm bore (95 cm MgB_2 magnet ID)
- 1.55 m (1.5 T) and 1.82 m (3.0 T) bore length – windings region
- < 10 ppm over a 45 cm DSV
- 5 gauss line < 3 m from center (1.5 T); < 4 m (3.0 T)
- Field temporal stability: drift < 0.1 ppm / hr
- Designs assume the magnets operate in persistent mode
- React-and-wind approach
- Conduction cooled
- 10 K operating temperature
- Active quench protection system

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1.5 & 3.0 T MgB_2 magnet design properties

Strength	1.5T		3.0T	
Type of Superconductor	MgB_2 design	NbTi guideline	MgB_2 design	NbTi guideline
Operating Temperature (K)	10	4.2	10	4.2
Amount of helium (bath cooling) (L)	0	1700	0	< 3000
Length (m)	1.55	1.25-1.70	1.81	1.60-1.80
Inner Diameter (m)	0.95		0.95	
Outer Diameter (m)	1.94	1.90-2.10	2.01	1.90-2.10
Peak-to-peak non-uniformity at 45 cm DSV (ppm)	9.6		9.7	
Radial 5 G footprint (m)	2.86	2.50	2.88	3.00
Axial 5 G footprint (m)	2.72	4.00	3.45	5.00
Inductance (H)	72.2		276.1	
Stored Energy (MJ)	2.28	2.00-4.00	8.8	10.00-15.00
Maximum Hoop Stress (MPa)	33.30		67.80	
Peak Magnetic Field (T)	2.68	< 9.00[a]	3.79	< 9.00
Coil operating current density $J_{op\ coil}$ (A mm^{-2})	116.23	< 250[a]	116.9	< 250
Amp-length (kA km)	14.8	< 25.00	31.8	< 60.00

- The MgB_2 MRI magnet designs allow for a 60 cm warm bore (leaving space for the coil formers, vacuum vessel, gradient coils and RF coils) and a length of less than 2 m.

a The NbTi wire has a critical current density of 250 A mm^{-2} at a peak magnetic field strength of 9 T while measured at 4.2 K. The maximum value of J_{coil} for such wire will be less than 250 A mm^{-2}.

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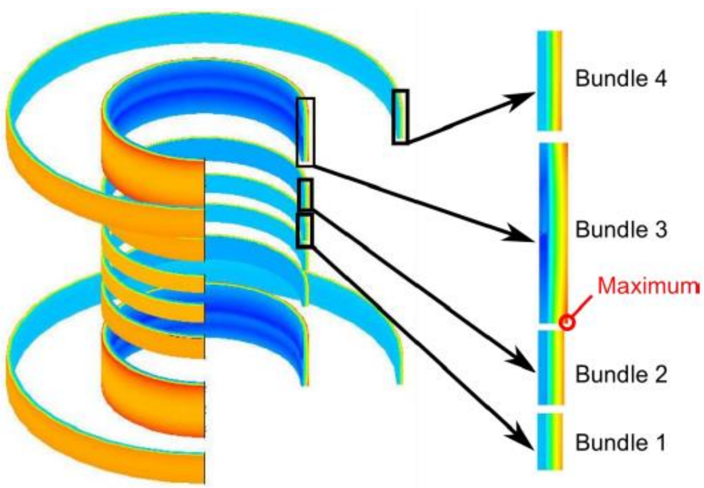
MgB_2 coil geometry

- Both magnet designs use eight magnet coil bundles: 6 driving the main magnetic field and 2 at a larger radius acting as shielding coils.
- Coil designs based on empirical formula $I_c(B,T)$ of standard MgB_2 wire
- I_{op} / I_c maximum 0.7



MgB_2 magnet design	1.5 T	3.0 T
MgB_2 wire type	A	B
I_{op}	251	252.5
total wire length, km	59	125.8
largest coil wire length, km	12	26.1
largest coil, layers	24	34
largest coil, turns	161	247

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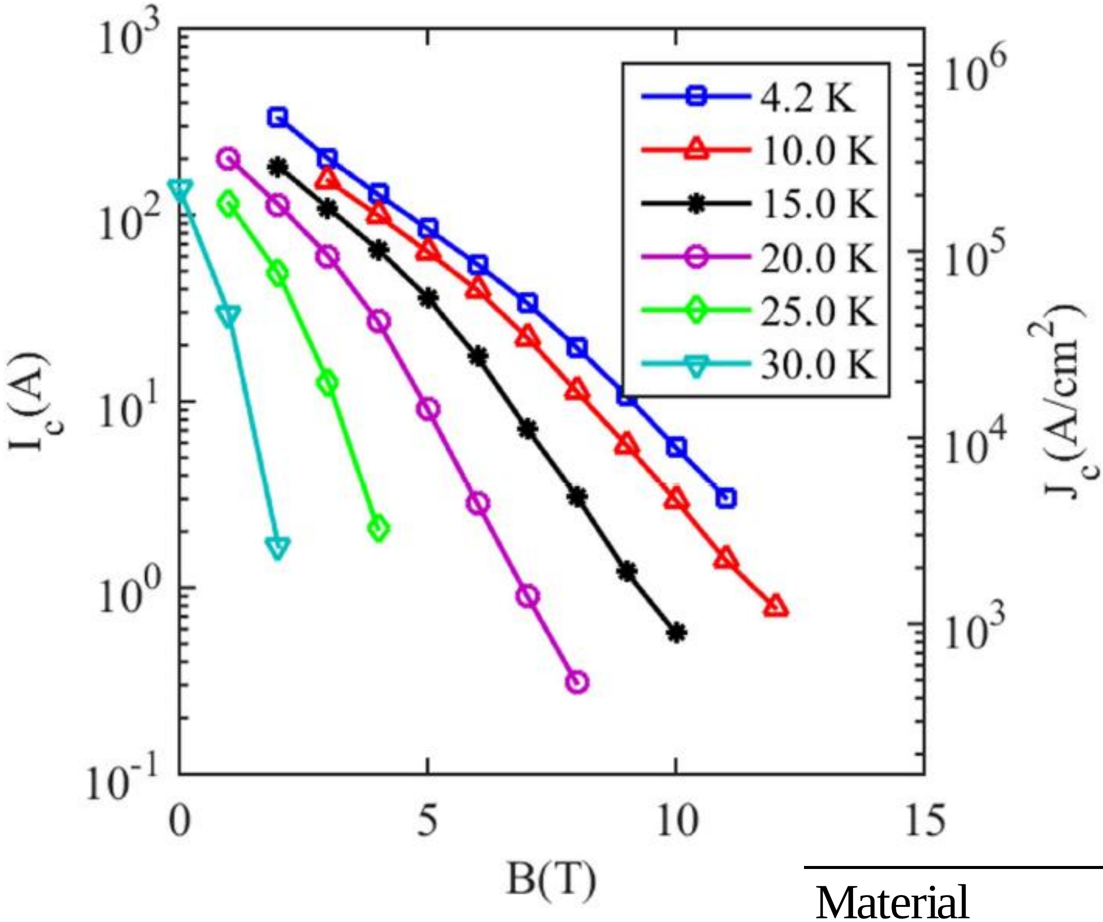
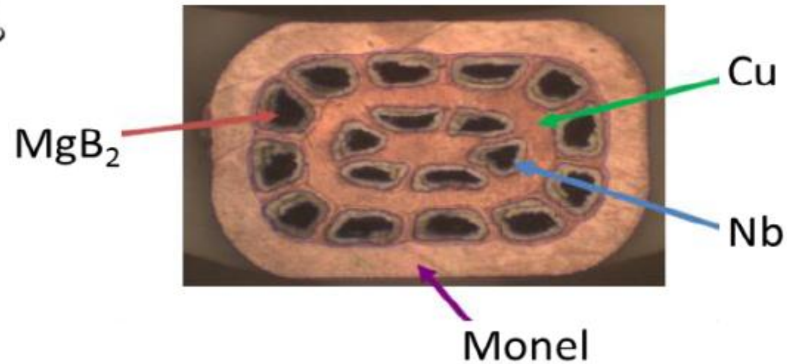
MgB_2 wire geometry and critical current



1.2 mm x 1.8 mm including braided insulation and impregnated with epoxy



Material	Wire A	Wire B
MgB_2	10%	15%
Cu	27%	42%
Nb	24%	20%
Monel	39%	23%

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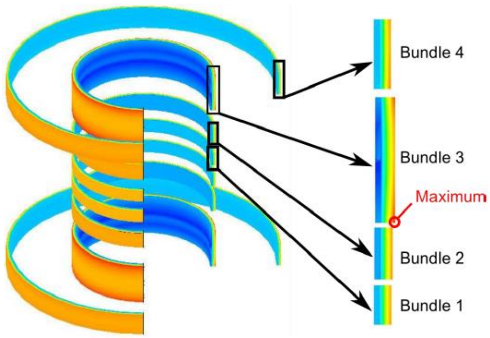
MgB_2 coil geometry

1.5 T

Coil	Polarity	r_c (m)	z_c (m)	N_r	N_z	B_{max} (T)	I_{op}/I_c	Length (km)
1	+	0.4978 416 045	0.082 882 2977	20	50	2.0455	0.407	3.13
2	+	0.496 704 1066	0.275 187 6475	21	66	2.1404	0.427	4.32
3	+	0.493 385 2656	0.630 551 4912	24	161	2.6869	0.562	12.0
4	−	0.962 692 7812	0.690 722 3289	19	88	1.9972	0.398	10.1
5	+	0.497 841 6045	−0.08 288 229 77	20	50	2.0455	0.407	3.13
6	+	0.496 704 1066	−0.275 187 6475	21	66	2.1404	0.427	4.32
7	+	0.493 385 2656	−0.630 551 4912	24	161	2.6869	0.562	12.0
8	−	0.962 692 7812	−0.690 722 3289	19	88	1.9972	0.398	10.1

I_{op} = 251 A



3.0 T

Coil	Polarity	r_c (m)	z_c (m)	N_r	N_z	B_{max}(T)	I_{op}/I_c	Length (km)
1	+	0.501 341 5842	0.081 080 8345	35	54	3.6936	0.628	5.95
2	+	0.506 790 4825	0.280 840 3580	33	92	3.6283	0.608	9.67
3	+	0.495 230 8503	0.684 796 3476	34	247	3.7978	0.663	26.1
4	−	0.993 824 9996	0.702 064 3276	24	141	2.7592	0.391	21.1
5	+	0.501 341 5842	−0.081 080 8345	35	54	3.6936	0.628	5.95
6	+	0.506 790 4825	−0.280 840 3580	33	92	3.6283	0.608	9.67
7	+	0.495 230 8503	−0.684 796 3476	34	247	3.7978	0.663	26.1
8	−	0.993 824 9996	−0.702 064 3276	24	141	2.7592	0.391	21.1

I_{op} = 252.5 A

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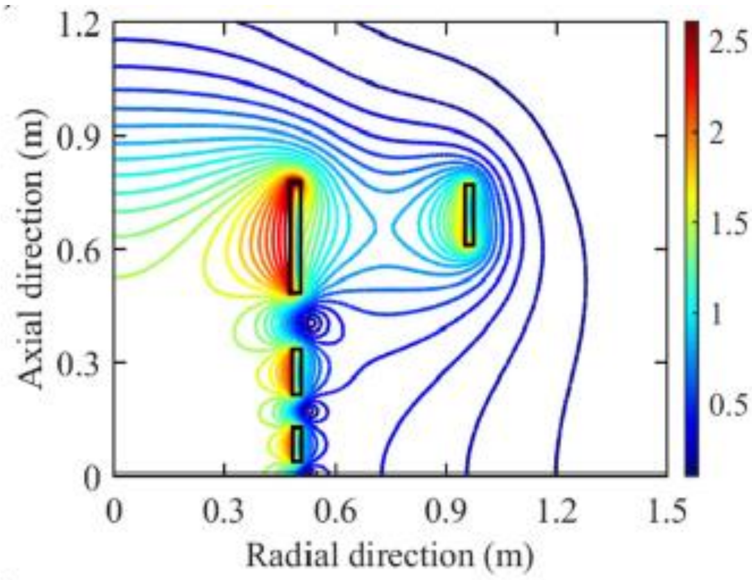
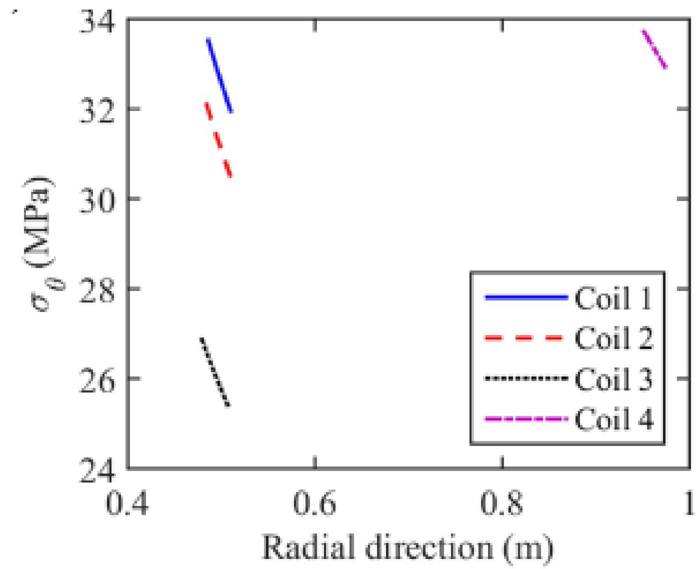
N_r layers x N_z turns

1.5 T MgB_2 magnetic design



Magnetic field distribution
2.68 T peak



Hoop stress distribution
33.30 MPa maximum

- Strongest magnetic field on wire is located in bundle 3
- Electromagnetic hoop stress resulting from Lorentz force calculated using Appleton method (ref: Caldwell *J. Phys. Appl. Phys.* **13** 1379 & Baig *Su.S.T.* **27** 125012)

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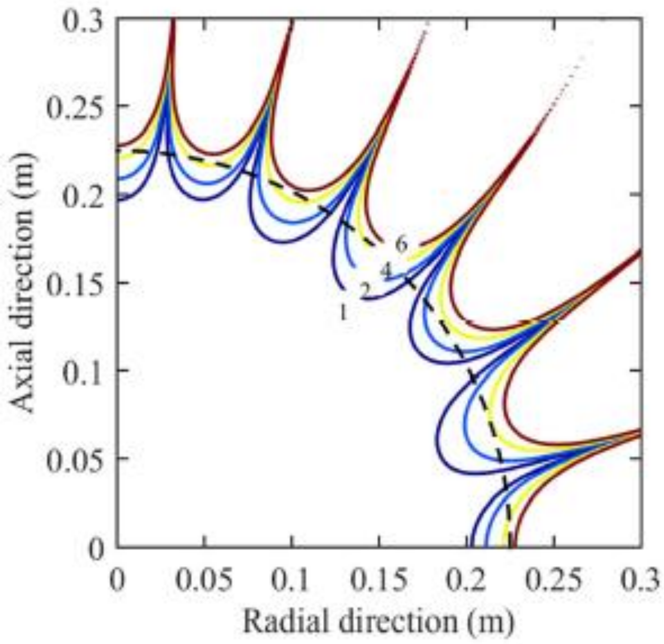
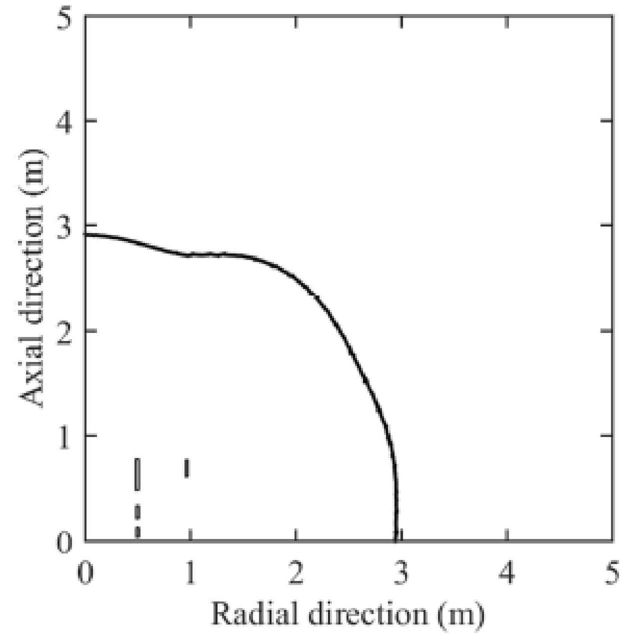
1.5 T MgB_2 magnetic design



DSV non-uniformity in ppm

4.8 ppm maximum deviation



5 gauss footprint

- Optimization method minimizes internal magnetic field moments for field homogeneity and minimizes external magnetic moments for limiting stray fields

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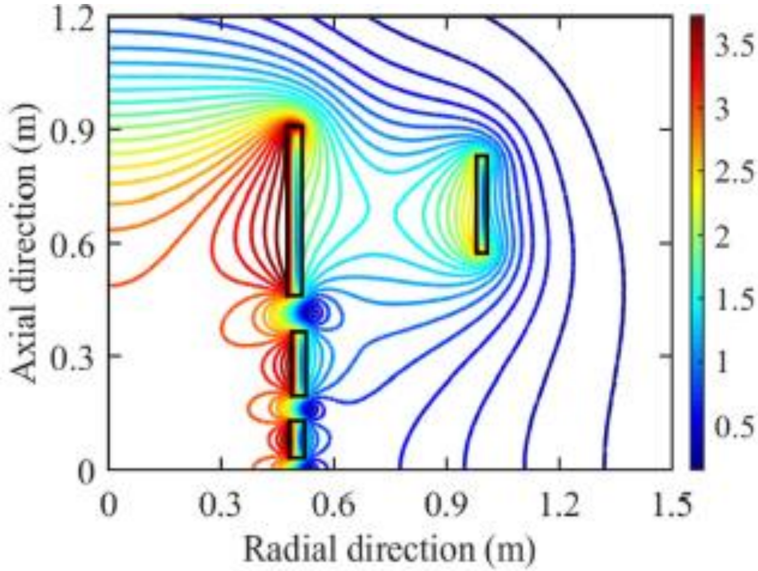
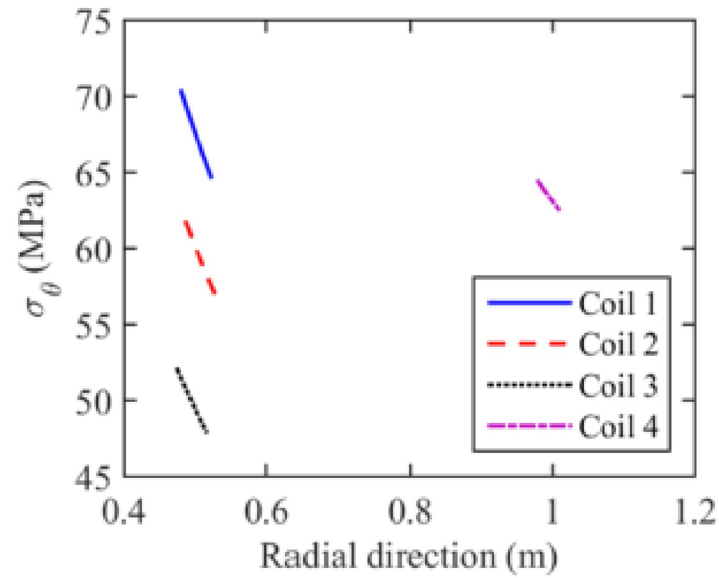
3.0 T MgB_2 magnetic design



Magnetic field distribution
3.79 T peak



Hoop stress distribution
67.80 MPa maximum

- Strongest magnetic field on wire is located in bundle 3
- Maximum hoop stress occurs in bundle 3
- 5.5 ppm maximum deviation
- 5 G footprint bigger than 1.5 T design (still under 4 m)

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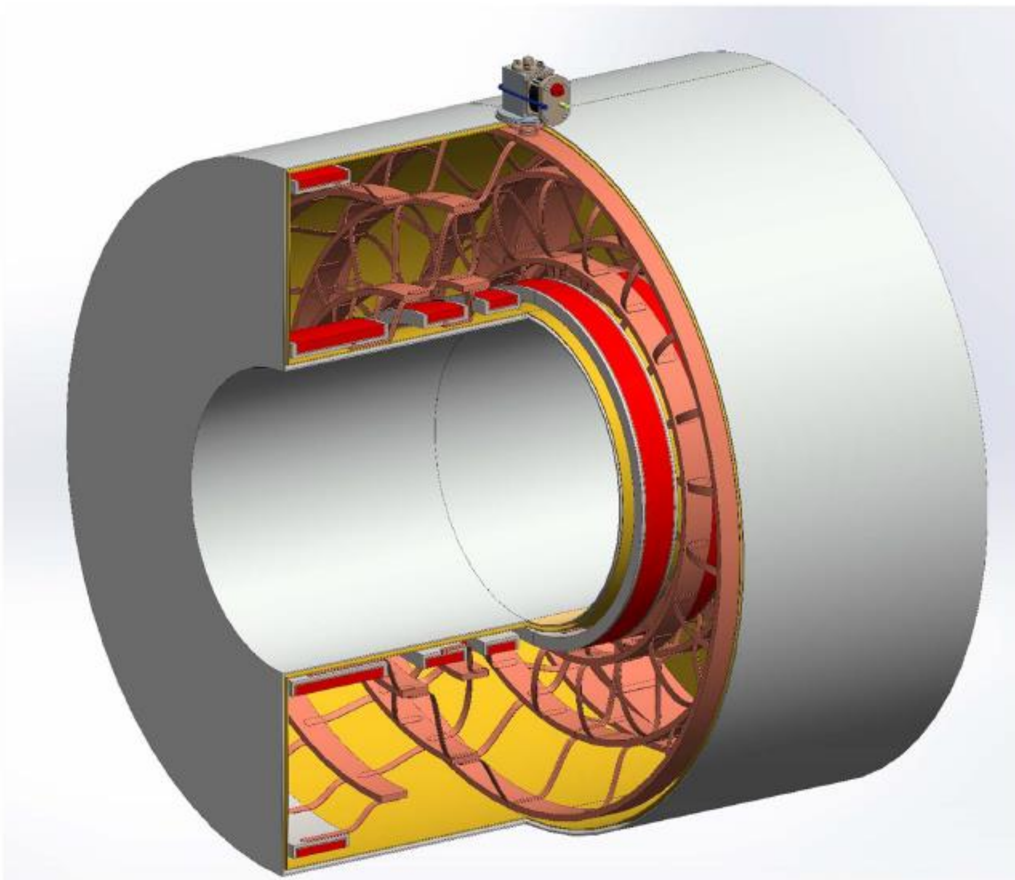
Conduction cooling



Cross section of the conduction cooling layout for the 1.5 T magnet design.

- Individual coils of wire (red) are wound around a stainless steel former.
- Copper straps connect the coils to copper cooling rings that are then connected to a 2-stage cryocooler.
- Layers of superinsulation (yellow) are placed between the magnet assembly and the wall of the vacuum vessel.

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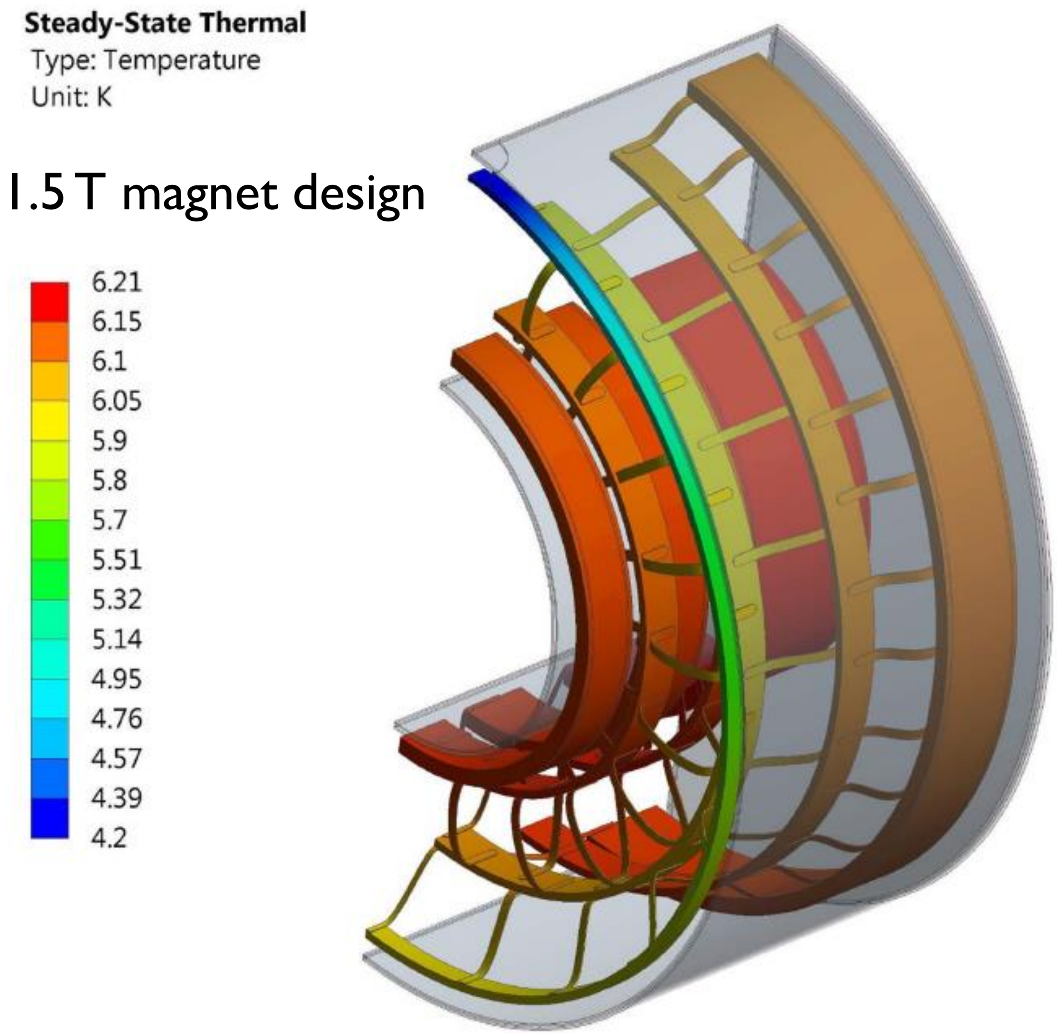
Conduction cooling



1.95 K temperature difference in magnet assembly

- 60 K cold shield
- Can use currently available cryocoolers for operating
  - first stage at 60 K
  - second stage at 4.2 K
- Radiative heat load on magnet assembly using FEA (ANSYS)
  - RVE approach used for thermal conductivity of MgB_2 wire+epoxy
- Also consider heat loss from mechanical supports, leads, etc.
- 56 W heat load at first stage
- 0.6 W heat load at second stage

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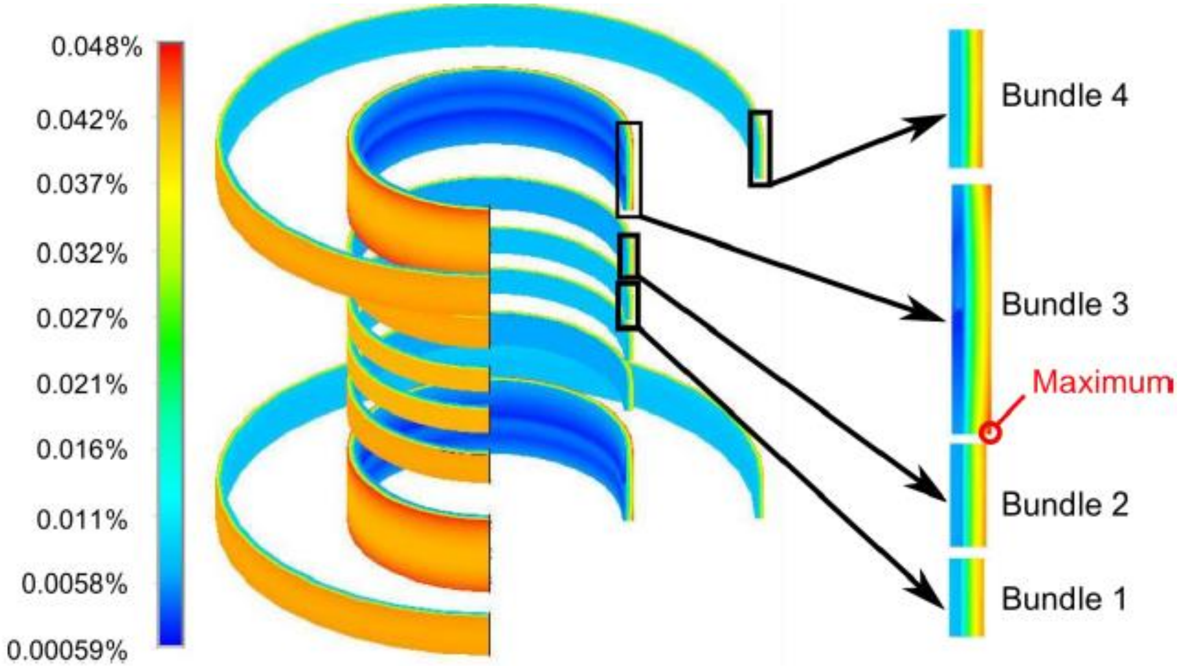
Mechanical design

Need to consider stress and strain during the manufacturing process and operation of magnet due to relative brittleness of MgB_2



First principle strain after the winding, cooling and energizing of the coils for 1.5 T MgB_2 magnet design

- 0.4% strain limit failure
- 0.2% safety factor strain limit criteria used
- FEA based on homogenized model (RVE approach) to compute *E*, *G*, ν, α of MgB_2 wire+epoxy
- Maximum strain of 0.048% at bundle 3 (0.067% for 3.0T magnet)
- Stress / strain due to quench covered in later slide

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Quench propagation

	1.5 T		1.5 T		3.0 T	
	Wire A (at T_{op} = 10 K)		Wire B (at T_{op} = 10 K)		Wire B (at T_{op} = 10 K)	
Quench location	[a]Coil 1	[b]Coil 3	[a]Coil 1	[b]Coil 3	[a]Coil 1	[b]Coil 3
I/I_c	0.227	0.562	0.151	0.375	0.188	0.663
MQE (J)	1.56	0.51	3.49	1.41	3.07	0.40
NZPV (cm s^{-1})	9.33	33.78	8.36	24.50	10.16	58.40

[a] On coil surface.
[b] At location of B_{max}.

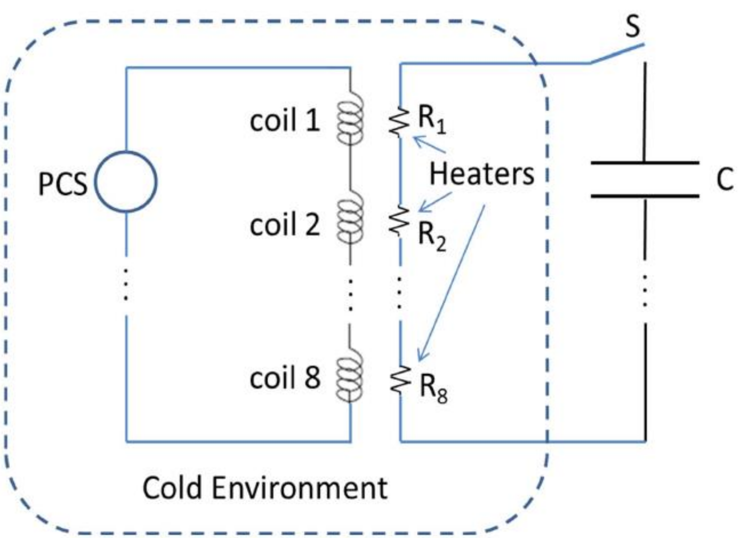
NZPV is in direction of current flow

As compared to NbTi:

- 1-10 mJ MQE
- 10-50 m/s NZPV

- MQE found by applying a 10mm x 2mm disturbance heater located on the outer surface of the coil. Pulse length set to 0.5 s. Simulation time of 3 s.
- For quench simulations, the wires are divided into small segments with the temperature and superconducting state of the segment recorded every 10 ms; the location of the leading edge of the quench as a function of time is measured.

Active quench protection



Schematic of an active quench protection system

- The slower NZPV of MgB_2 makes it harder to protect such a magnet during a quench: contributes to a faster rise in temperature at the location of the quenched hot spot.
- Intentionally quench as much of the magnet as quickly as possible in order to distribute magnetic energy as evenly as possible.
- Set of quench heaters on each coil that are powered by a charged capacitor. The switch to the capacitor is activated by the detection of a small voltage (~100mV) developed across one of the coils.
- Heaters are placed around the outside of the coils

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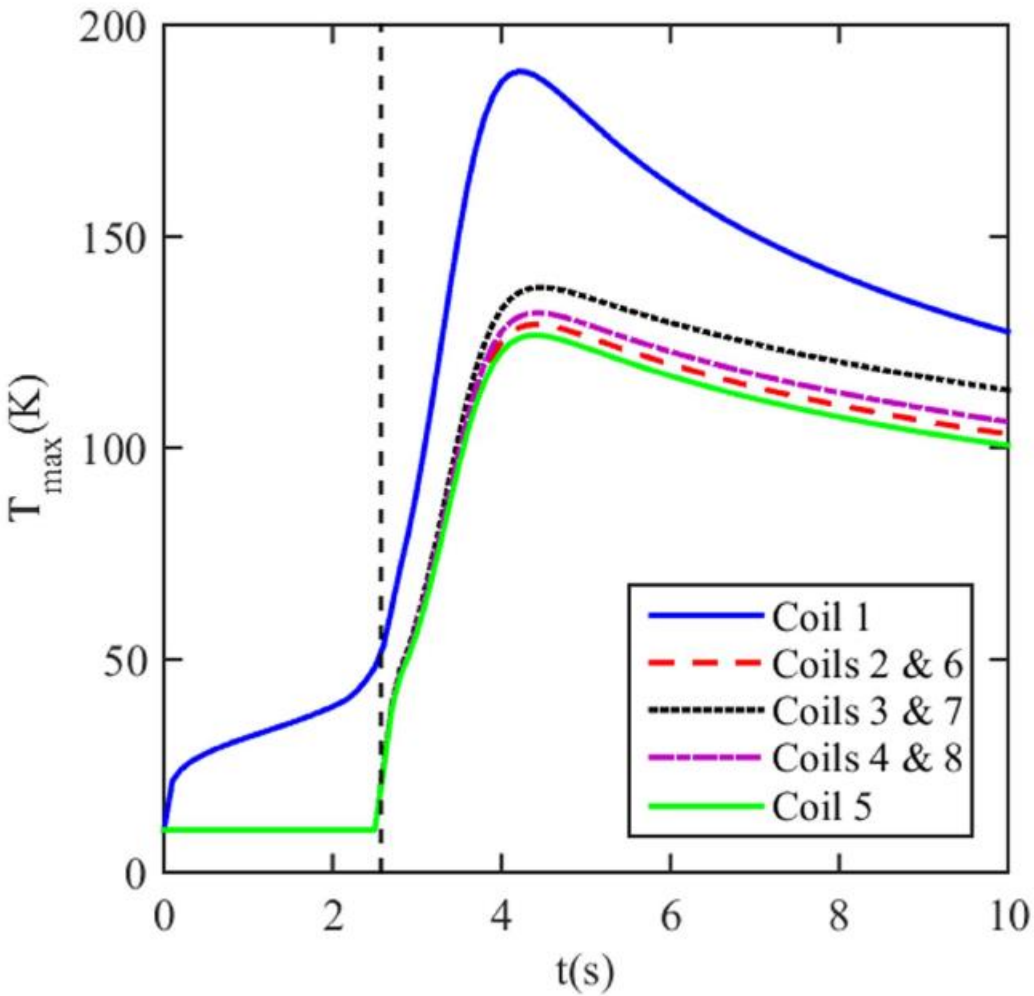
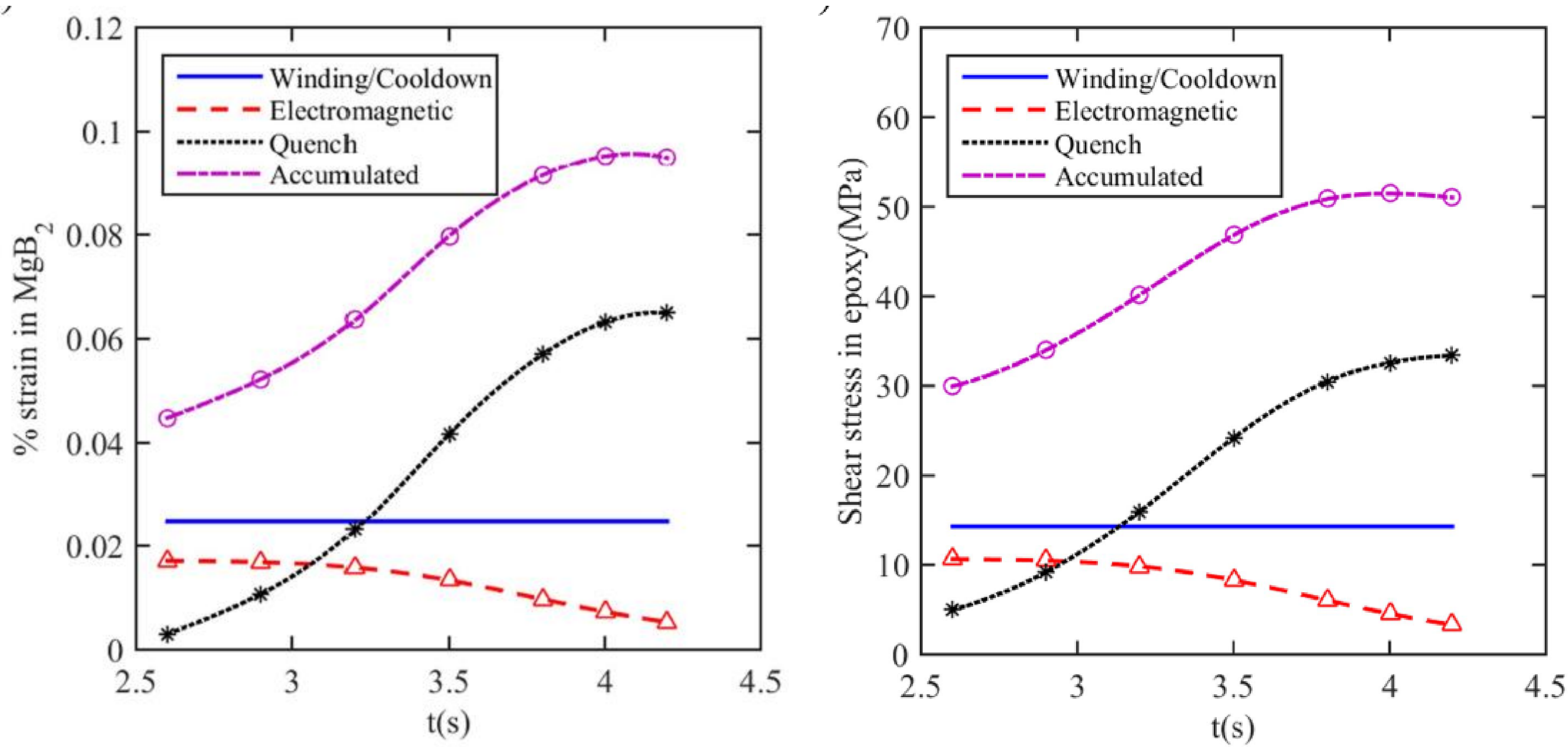
Quench simulations



- The maximum temperature in each coil bundle as a function of time for the 1.5 T magnet design. The quench protection is triggered when the voltage on coil 1 reaches 100 mV.
- For the 1.5 T magnet, the maximum temperature rise can be kept below 200 K by injecting a total of 34.4 kJ into the outer layers of the coils within 0.2 s.

Quench simulations



Strains and stresses calculated in ANSYS during the quench simulation of the 1.5 T magnet: tensile in MgB_2 (*left*); shear in epoxy (*right*)

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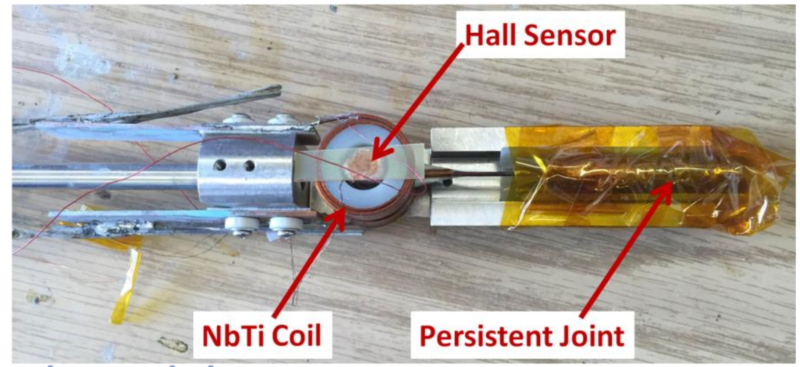
3.0 T magnet: max strain in MgB_2 = 0.0697
max shear stress in epoxy = 44 MPa

Decay measurements of persistent joints

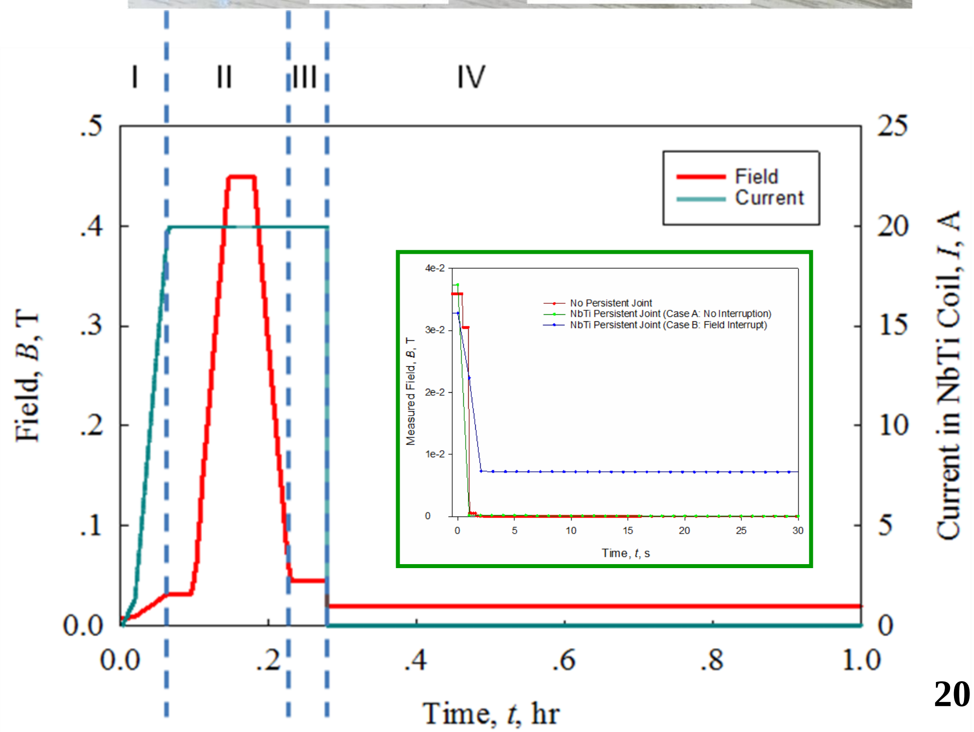
- While further improvement in critical current of joints is still in process, it is important to measure R at values below 10^{-10} ohm
- Thus, a decay rig was needed, as well as some initial testing and verification using NbTi test joints.



Protocol:

I. Use NbTi coil to generate B_{loop} (I = 20 A)
II. Increase the B_{ext} to 3 T (pushes joint > SC)
III. Drop B_{ext} to 0.
IV. Turn off NbTi coil rapidly.

Note: Only the field in step IV indicates the field generated by the test joint.



- Blue curve at right shows current change in the NbTi coil.
- Red curve indicates the field reading by the Hall sensor.
- Expansion of decay region shown in green insert box

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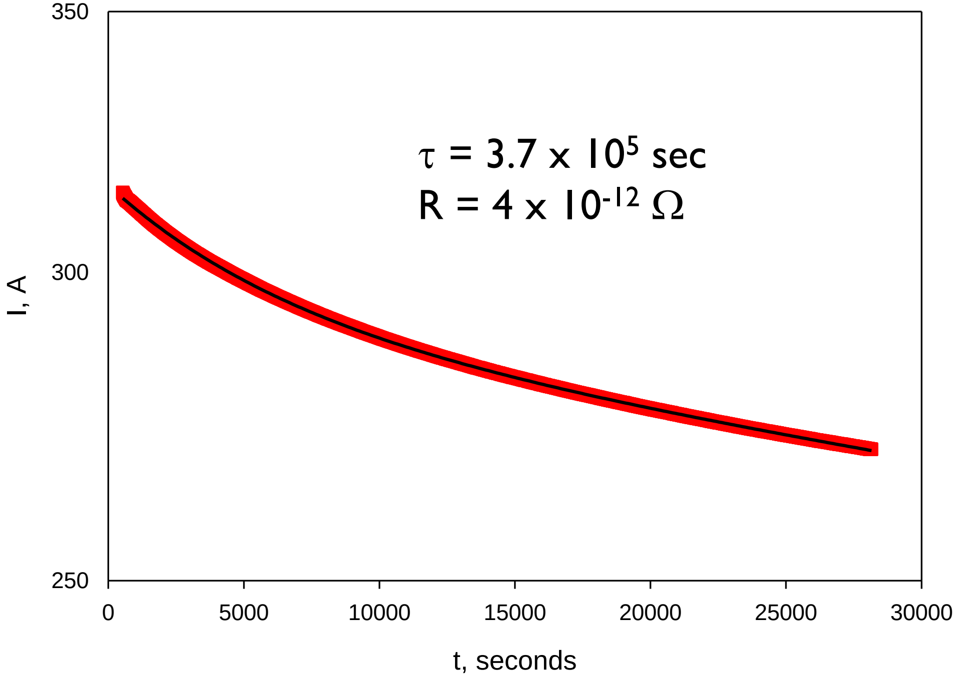
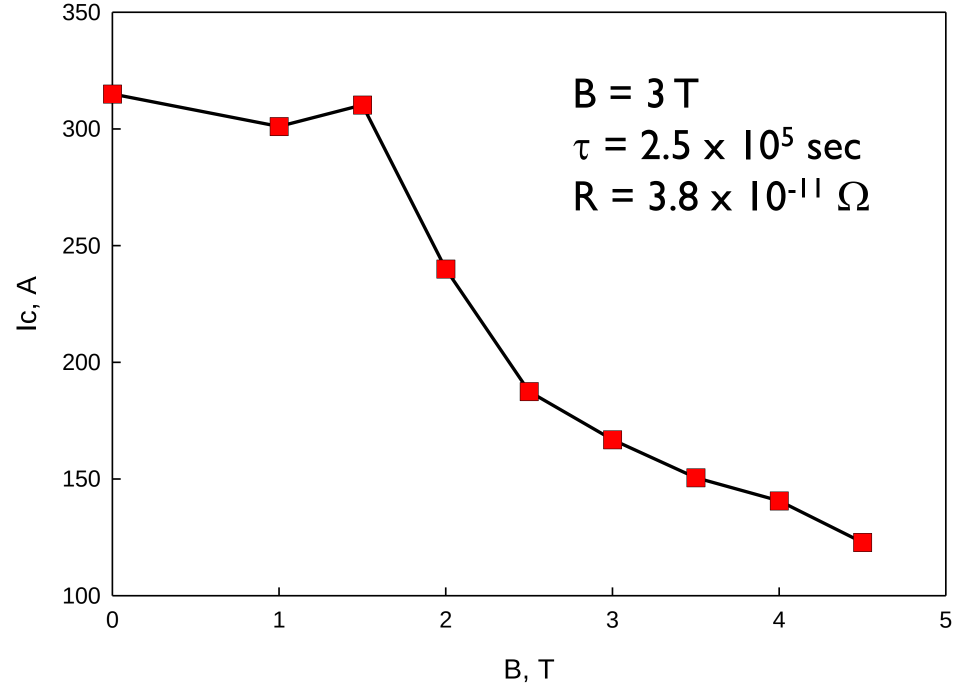
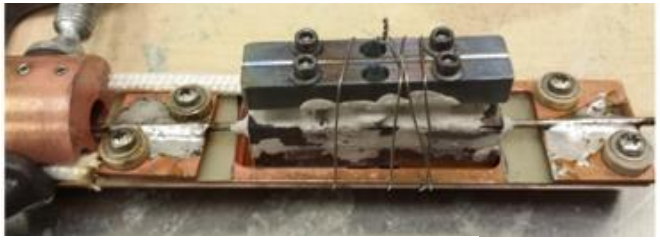
Persistent joint measurements



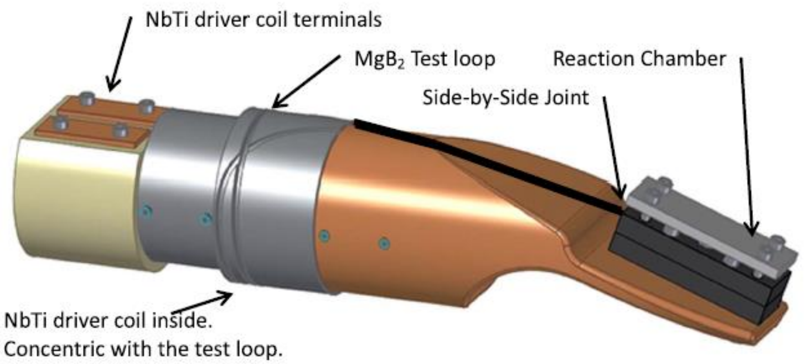
Decay of persistent current in MgB_2 W&R style joint at zero applied field (4.2 K)



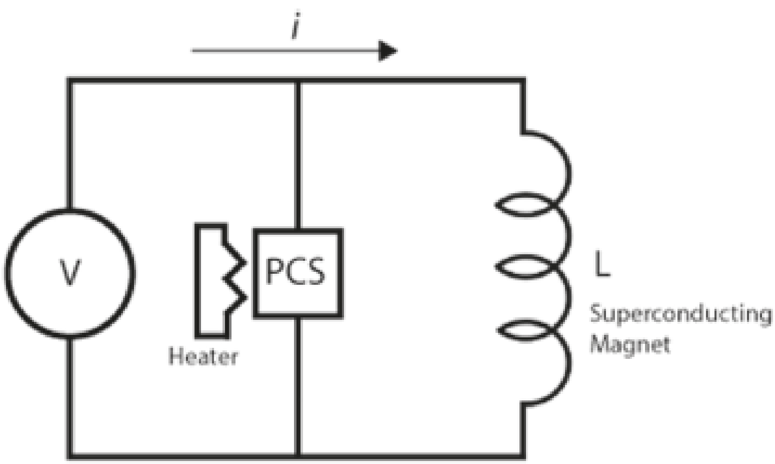
Initial persistent current as a function of field at 4.2 K



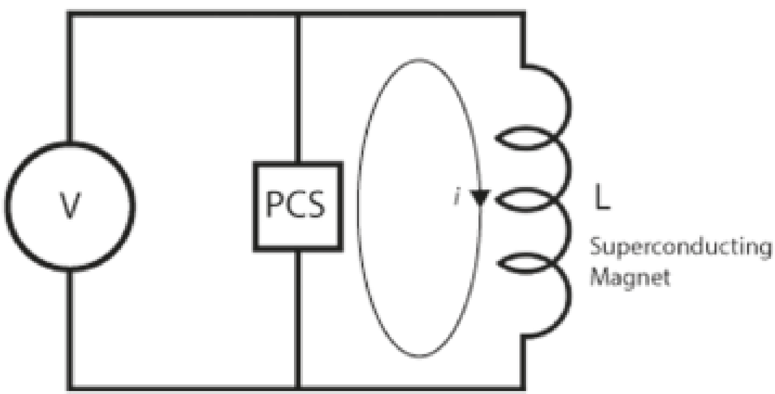
Need both side-to-side and end-to-end



Persistent switch for MgB_2 MRI magnet system

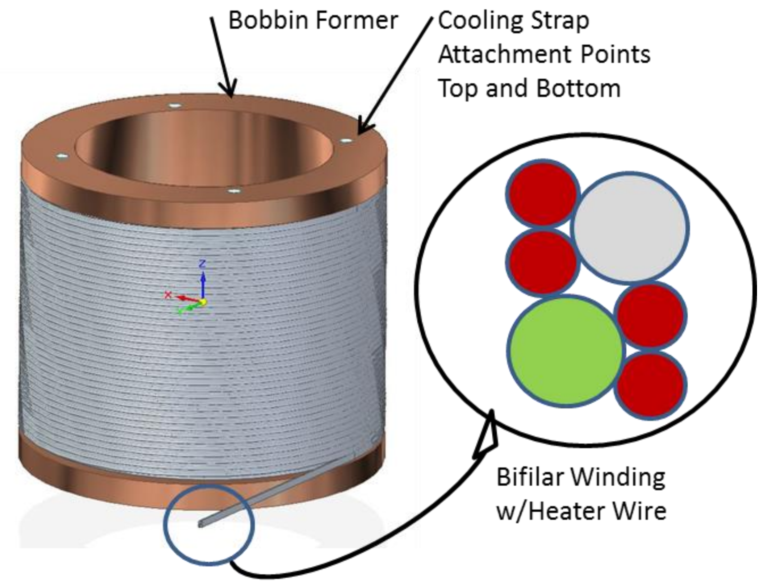


During charging of magnet



PCS circuit when heater is removed

- Copper bobbin
- Non-inductive wrapping
- Close-packed winding
- CuNi matrix MgB_2 wire
- Shunt current fraction 0.1%
- R_{switch} = 10.0 Ω (1.5 T); = 38.3 Ω (3.0 T)



For 1.5 T MRI, and switch operating at 60 K:

- Coil OD = 28.8 cm; coil height = 10 cm
- Wire resistivity = 34.4 nΩ-m
- Wire length = 229 m
- Ramp-up heater = 10 W
- Ramp-up time = 37 min
- Cool-down time = 70 min

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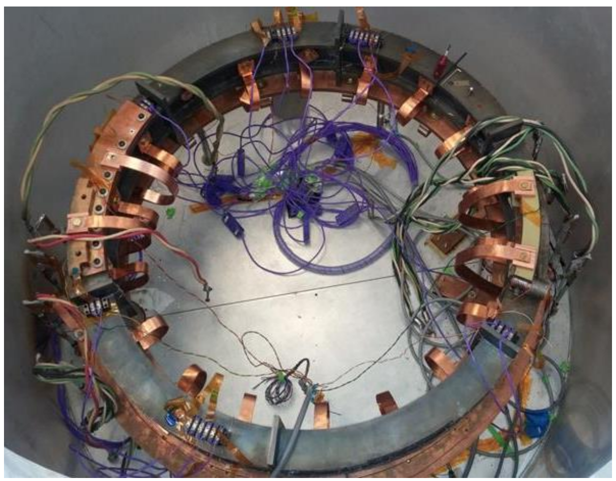
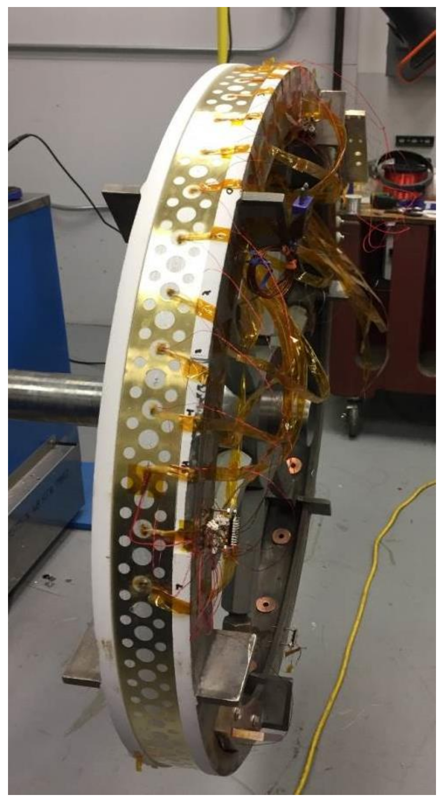
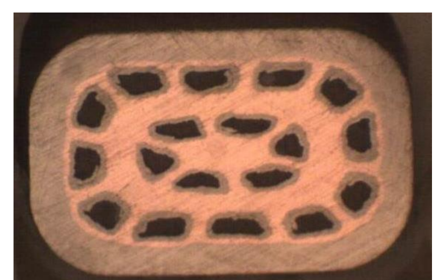
Test coil for validating model

- React-and-wind, conduction-cooled segment coil is under testing.
  - Conduction cooled via two Sumitomo cryocoolers with 1.5 W each at 4 K.
  - Spot heaters are used to induce quenches for normal zone propagation properties studies.
  - A coil protection structure was embedded into the coil perimeter which is fired upon quench detection.





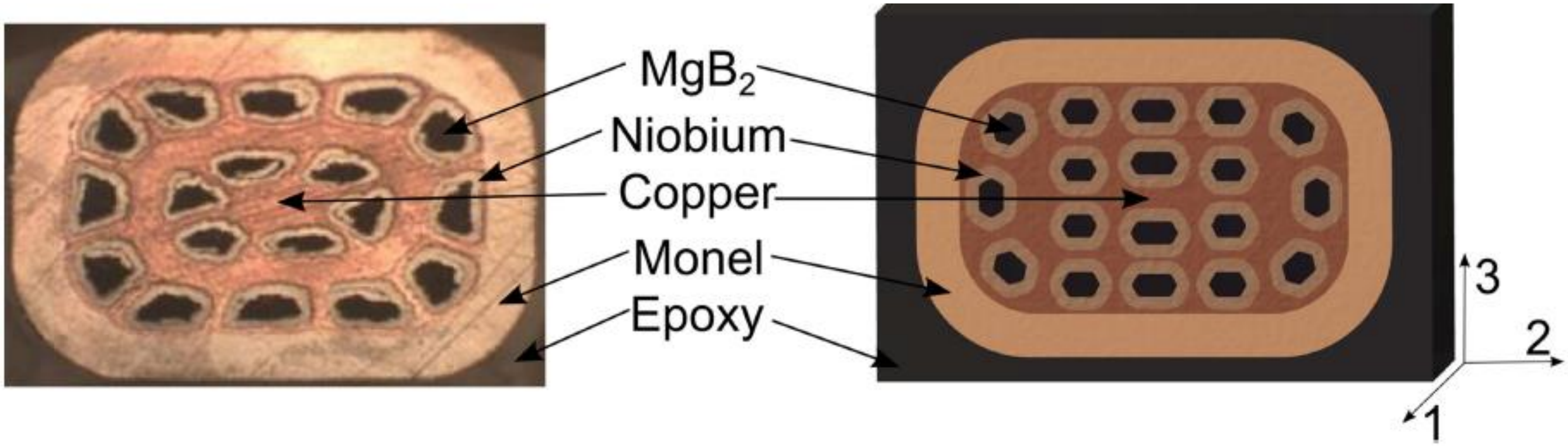
- I_{op} **= 200 A**
- B_w **= 1.5 T (20 K)**
- **Coil OD = 0.86 m**
- **Coil height = 5.1 cm**
- **636 turns**
- **22 layers**
- **29 turns/layer**
- **Conductor length = 1744 m**



---- thank you for your attention

---- extry slides

Homogenized model - RVE



Modulus of elasticity (θ direction)	112 GPa	112 GPa
Modulus of elasticity (z direction)	57.9 GPa	57.8 GPa
Modulus of elasticity (r direction)	59.6 GPa	59.5 GPa
Shear modulus ($G_{\theta z}$)	17.5 GPa	17.9 GPa
Shear modulus (G_{zr})	13.4 GPa	13.3 GPa
Shear modulus ($G_{r\theta}$)	18 GPa	17.4 GPa
Poisson's ratio ($\nu_{\theta z}$)	0.26	0.259
Poisson's ratio (ν_{zr})	0.288	0.288
Poisson's ratio ($\nu_{r\theta}$)	0.255	0.254
Average thermal expansion coefficient (10–298 K) (α_1)	10.1 μm m^{-1} K^{-1}	9.32 μm m^{-1} K^{-1}
Average thermal expansion coefficient (α_2)	12.9 μm m^{-1} K^{-1}	12.5 μm m^{-1} K^{-1}
Average thermal expansion coefficient (α_3)	12.6 μm m^{-1} K^{-1}	12.3 μm m^{-1} K^{-1}

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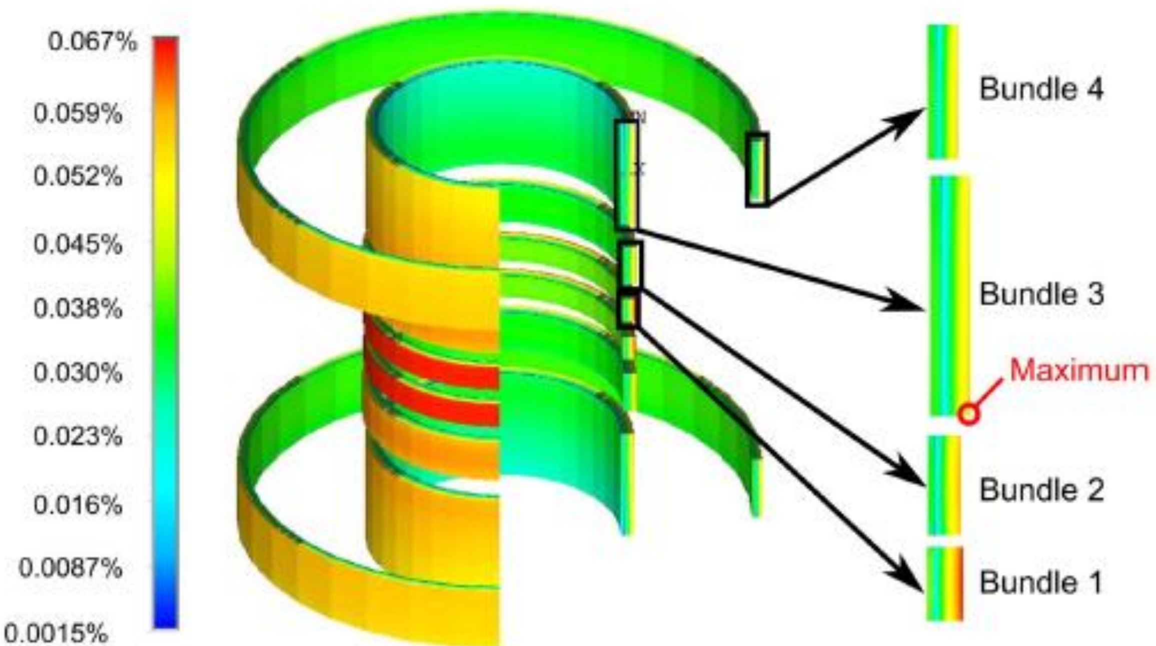
representative volume element (RVE)

Mechanical design

- Need to consider stress and strain during the manufacturing process and operation of magnet due to relative brittleness of MgB_2

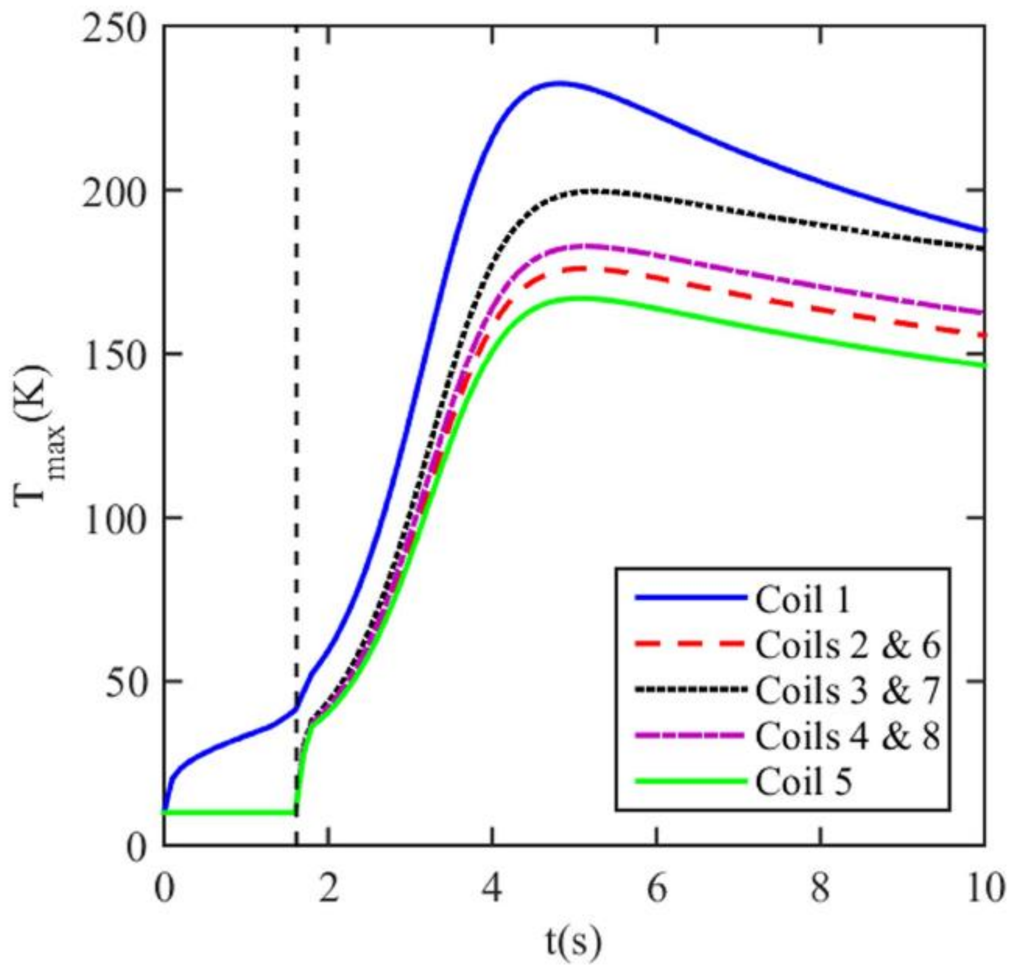


First principle strain after the winding, cooling and energizing of the coils for 3.0 T MgB_2 magnet design

- 0.4% strain limit failure
- 0.2% safety factor strain limit criteria used
- FEA based on homogenized model (RVE approach) to compute E, G, ν, α of MgB_2 wire+epoxy
- Maximum strain of 0.048% at bundle 3 (0.067% for 3.0T magnet)
- Stress / strain due to quench covered in later slide

Hyper Tech

Quench simulations



- The maximum temperature in each coil bundle as a function of time for the 3.0 T magnet design. The quench protection is triggered when the voltage on coil 1 reaches 100 mV.

Hyper Tech

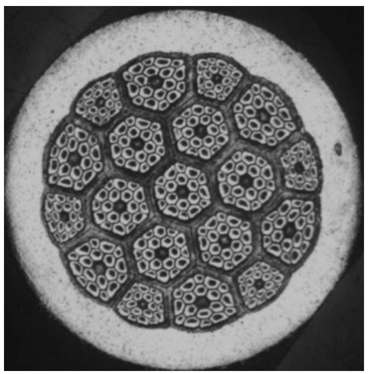
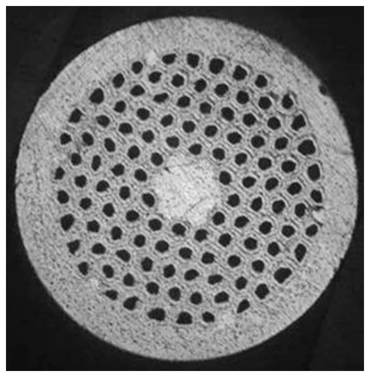
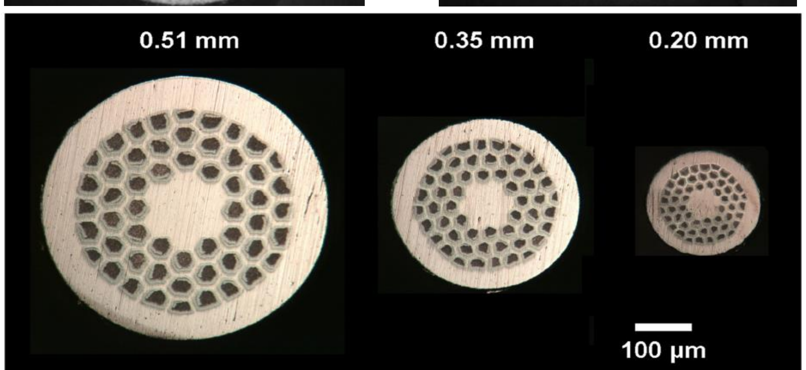
Low AC loss MgB_2 conductor development

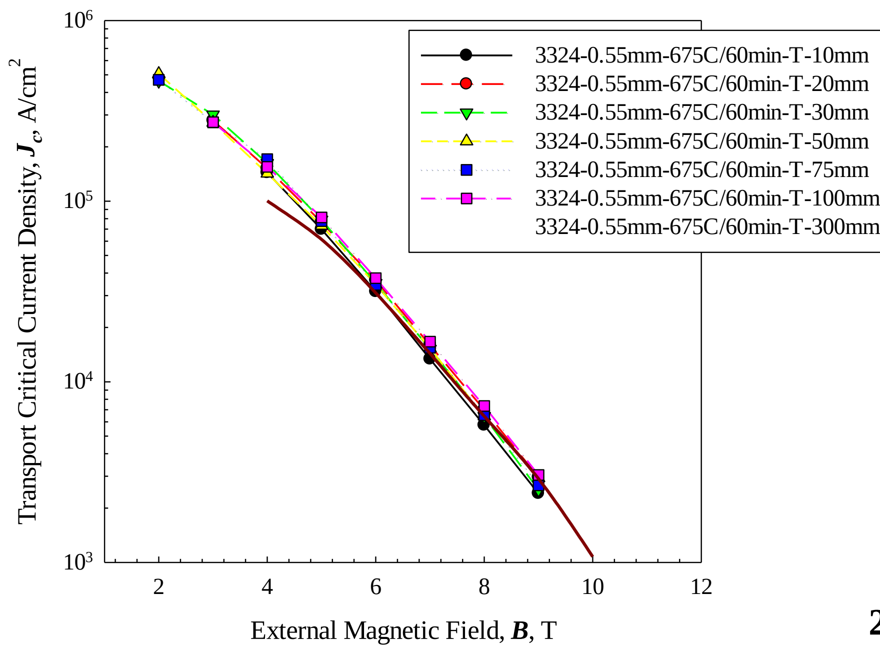
- **Original goal was 10 µm filaments for stators in the 5-200 Hz range.**

Loss contributions

- Hysteretic ▶ Filament diameter d_{eff} = 10 µm
- Coupling ▶ L_p = 5 mm; ▶ Matrix resistivity ρ_{eff} >> Cu
- Transport current ▶ Non-magnetic sheath materials

- J_c maintained with n filaments = 100 – 300.
- J_c measured with 10 µm filaments at 0.29 mm. Work progressing to get obtain 10 µm filaments with larger wire diameters.
- J_c maintained with twist pitches as low as 5 mm.



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