Design and development of conduction cooled MgB$_2$ magnets for 1.5 and 3.0T full body MRI systems
Partners and Collaborators

Matt Rindfleisch
Mike Tomsic
David Doll
Robert Mendris
CJ Thong
Xuan Peng

Tanvir Baig
Abdullah Al Amin
Robert J. Deissler
Laith Sabri
Charles Poole
Robert W. Brown
Ozan Akkus
Michael Martens

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 MgB₂ 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
Superconductivity Industry Experience

Experience in conductor manufacturing, coil fabrication or both:
- BSCCO
- MgB$_2$
- Nb$_3$Al
- Nb$_3$Sn
- 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
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
### 1.5 & 3.0 T MgB$_2$ magnet design properties

<table>
<thead>
<tr>
<th>Strength</th>
<th>1.5T</th>
<th>3.0T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Superconductor</td>
<td>MgB$_2$ design</td>
<td>NbTi guideline</td>
</tr>
<tr>
<td>Operating Temperature (K)</td>
<td>10</td>
<td>4.2</td>
</tr>
<tr>
<td>Amount of helium (bath cooling) (L)</td>
<td>0</td>
<td>1700</td>
</tr>
<tr>
<td>Length (m)</td>
<td>1.55</td>
<td>1.25-1.70</td>
</tr>
<tr>
<td>Inner Diameter (m)</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Outer Diameter (m)</td>
<td>1.94</td>
<td>1.90-2.10</td>
</tr>
<tr>
<td>Peak-to-peak non-uniformity at 45 cm DSV (ppm)</td>
<td>9.6</td>
<td>9.7</td>
</tr>
<tr>
<td>Radial 5 G footprint (m)</td>
<td>2.86</td>
<td>2.50</td>
</tr>
<tr>
<td>Axial 5 G footprint (m)</td>
<td>2.72</td>
<td>4.00</td>
</tr>
<tr>
<td>Inductance (H)</td>
<td>72.2</td>
<td></td>
</tr>
<tr>
<td>Stored Energy (MJ)</td>
<td>2.28</td>
<td>2.00-4.00</td>
</tr>
<tr>
<td>Maximum Hoop Stress (MPa)</td>
<td>33.30</td>
<td></td>
</tr>
<tr>
<td>Peak Magnetic Field (T)</td>
<td>2.68</td>
<td>&lt; 9.00$^a$</td>
</tr>
<tr>
<td>Coil operating current density $J_{\text{op coil}}$ (A mm$^{-2}$)</td>
<td>116.23</td>
<td>&lt; 250$^a$</td>
</tr>
<tr>
<td>Amp-length (kA km)</td>
<td>14.8</td>
<td>&lt; 25.00</td>
</tr>
</tbody>
</table>

- 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 $J_{\text{coil}}$ for such wire will be less than 250 A mm$^{-2}$.
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

<table>
<thead>
<tr>
<th>MgB$_2$ magnet design</th>
<th>1.5 T</th>
<th>3.0 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgB$_2$ wire type</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>$I_{op}$</td>
<td>251</td>
<td>252.5</td>
</tr>
<tr>
<td>total wire length, km</td>
<td>59</td>
<td>125.8</td>
</tr>
<tr>
<td>largest coil wire length, km</td>
<td>12</td>
<td>26.1</td>
</tr>
<tr>
<td>largest coil, layers</td>
<td>24</td>
<td>34</td>
</tr>
<tr>
<td>largest coil, turns</td>
<td>161</td>
<td>247</td>
</tr>
</tbody>
</table>
MgB$_2$ wire geometry and critical current

<table>
<thead>
<tr>
<th>Material</th>
<th>Wire A</th>
<th>Wire B</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgB$_2$</td>
<td>10%</td>
<td>15%</td>
</tr>
<tr>
<td>Cu</td>
<td>27%</td>
<td>42%</td>
</tr>
<tr>
<td>Nb</td>
<td>24%</td>
<td>20%</td>
</tr>
<tr>
<td>Monel</td>
<td>39%</td>
<td>23%</td>
</tr>
</tbody>
</table>

1.2 mm x 1.8 mm including braided insulation and impregnated with epoxy
### MgB$_2$ Coil Geometry

#### 1.5 T

<table>
<thead>
<tr>
<th>Coil</th>
<th>Polarity</th>
<th>$r_c$ (m)</th>
<th>$z_c$ (m)</th>
<th>$N_r$</th>
<th>$N_z$</th>
<th>$B_{\text{max}}$ (T)</th>
<th>$I_{\text{op}}/I_c$</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+</td>
<td>0.4978 416 045</td>
<td>0.082 882 2977</td>
<td>20</td>
<td>50</td>
<td>2.0455</td>
<td>0.407</td>
<td>3.13</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>0.496 704 1066</td>
<td>0.275 187 6475</td>
<td>21</td>
<td>66</td>
<td>2.1404</td>
<td>0.427</td>
<td>4.32</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>0.493 385 2656</td>
<td>0.630 551 4912</td>
<td>24</td>
<td>161</td>
<td>2.6869</td>
<td>0.562</td>
<td>12.0</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>0.962 692 7812</td>
<td>0.690 722 3289</td>
<td>19</td>
<td>88</td>
<td>1.9972</td>
<td>0.398</td>
<td>10.1</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
<td>0.497 841 6045</td>
<td>−0.082 288 22977</td>
<td>20</td>
<td>50</td>
<td>2.0455</td>
<td>0.407</td>
<td>3.13</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>0.496 704 1066</td>
<td>−0.275 187 6475</td>
<td>21</td>
<td>66</td>
<td>2.1404</td>
<td>0.427</td>
<td>4.32</td>
</tr>
<tr>
<td>7</td>
<td>+</td>
<td>0.493 385 2656</td>
<td>−0.630 551 4912</td>
<td>24</td>
<td>161</td>
<td>2.6869</td>
<td>0.562</td>
<td>12.0</td>
</tr>
<tr>
<td>8</td>
<td>−</td>
<td>0.962 692 7812</td>
<td>−0.690 722 3289</td>
<td>19</td>
<td>88</td>
<td>1.9972</td>
<td>0.398</td>
<td>10.1</td>
</tr>
</tbody>
</table>

#### 3.0 T

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

$I_{\text{op}} = 251$ A

$I_{\text{op}} = 252.5$ A

$N_r$ layers $\times N_z$ 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
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
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)
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.
Conduction cooling

- 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

1.9 T magnet design

Steady-State Thermal
Type: Temperature
Unit: K

1.95 K temperature difference in magnet assembly
Mechanical design

Need to consider stress and strain during the manufacturing process and operation of magnet due to relative brittleness of MgB$_2$  

- 0.4% strain limit failure  
- 0.2% safety factor strain limit criteria used  
- FEA based on homogenized model (RVE approach) to compute $E$, $G$, $\nu$, $\alpha$ 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  

First principle strain after the winding, cooling and energizing of the coils for 1.5 T MgB$_2$ magnet design
# Quench propagation

<table>
<thead>
<tr>
<th>Quench location</th>
<th>Wire A (at $T_{op} = 10 \text{ K}$)</th>
<th>Wire B (at $T_{op} = 10 \text{ K}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^a$Coil 1</td>
<td>$^b$Coil 3</td>
</tr>
<tr>
<td>$I/I_c$</td>
<td>0.227</td>
<td>0.562</td>
</tr>
<tr>
<td>MQE (J)</td>
<td>1.56</td>
<td>0.51</td>
</tr>
<tr>
<td>NZPV (cm s$^{-1}$)</td>
<td>9.33</td>
<td>33.78</td>
</tr>
<tr>
<td></td>
<td>$^a$Coil 1</td>
<td>$^b$Coil 3</td>
</tr>
<tr>
<td></td>
<td>0.151</td>
<td>0.375</td>
</tr>
<tr>
<td></td>
<td>3.49</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>8.36</td>
<td>24.50</td>
</tr>
<tr>
<td></td>
<td>0.188</td>
<td>0.663</td>
</tr>
<tr>
<td></td>
<td>3.07</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>10.16</td>
<td>58.40</td>
</tr>
</tbody>
</table>

$^a$ 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

- 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 ($\sim$100mV) developed across one of the coils.
- Heaters are placed around the outside of the coils.

Schematic of an active quench protection system
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.
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)

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.
Persistant joint measurements

\[ \tau = 3.7 \times 10^5 \text{ sec} \]
\[ R = 4 \times 10^{-12} \Omega \]

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

\[ B = 3 \text{ T} \]
\[ \tau = 2.5 \times 10^5 \text{ sec} \]
\[ R = 3.8 \times 10^{-11} \Omega \]

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

NbTi driver coil terminals
MgB$_2$ Test loop
Side-by-Side Joint
Reaction Chamber

NbTi driver coil inside. Concentric with the test loop.
Persistent switch for MgB$_2$ MRI magnet system

- Copper bobbin
- Non-inductive wrapping
- Close-packed winding
- CuNi matrix MgB$_2$ wire
- Shunt current fraction 0.1%
- $R_{\text{switch}} = 10.0 \ \Omega \ (1.5 \ T) ; = 38.3 \ \Omega \ (3.0 \ T)$

For 1.5 T MRI, and switch operating at 60 K:
- Coil OD = 28.8 cm; coil height = 10 cm
- Wire resistivity = 34.4 n$\Omega$-m
- Wire length = 229 m
- Ramp-up heater = 10 W
- Ramp-up time = 37 min
- Cool-down time = 70 min
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**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity (θ direction)</td>
<td>112 GPa</td>
<td>112 GPa</td>
</tr>
<tr>
<td>Modulus of elasticity (z direction)</td>
<td>57.9 GPa</td>
<td>57.8 GPa</td>
</tr>
<tr>
<td>Modulus of elasticity (r direction)</td>
<td>59.6 GPa</td>
<td>59.5 GPa</td>
</tr>
<tr>
<td>Shear modulus (Gθ,z)</td>
<td>17.5 GPa</td>
<td>17.9 GPa</td>
</tr>
<tr>
<td>Shear modulus (Gζφ)</td>
<td>13.4 GPa</td>
<td>13.3 GPa</td>
</tr>
<tr>
<td>Shear modulus (Grθ)</td>
<td>18 GPa</td>
<td>17.4 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio (νθ,z)</td>
<td>0.26</td>
<td>0.259</td>
</tr>
<tr>
<td>Poisson’s ratio (νζφ)</td>
<td>0.288</td>
<td>0.288</td>
</tr>
<tr>
<td>Poisson’s ratio (νrθ)</td>
<td>0.255</td>
<td>0.254</td>
</tr>
<tr>
<td>Average thermal expansion coefficient (10–298 K) (α1)</td>
<td>10.1 μm m⁻¹ K⁻¹</td>
<td>9.32 μm m⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Average thermal expansion coefficient (α2)</td>
<td>12.9 μm m⁻¹ K⁻¹</td>
<td>12.5 μm m⁻¹ K⁻¹</td>
</tr>
<tr>
<td>Average thermal expansion coefficient (α3)</td>
<td>12.6 μm m⁻¹ K⁻¹</td>
<td>12.3 μm m⁻¹ K⁻¹</td>
</tr>
</tbody>
</table>
Mechanical design

- Need to consider stress and strain during the manufacturing process and operation of magnet due to relative brittleness of MgB$_2$

- 0.4% strain limit failure
- 0.2% safety factor strain limit criteria used
- FEA based on homogenized model (RVE approach) to compute $E$, $G$, $\nu$, $\alpha$ 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

First principle strain after the winding, cooling and energizing of the coils for 3.0 T MgB$_2$ magnet design
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.
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 $\rho_{eff} >> \text{Cu}$

- **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.

**Graph:**

- Shows the relationship between external magnetic field ($B$, T) and transport critical current density ($J_c$, A/cm$^2$).

**Table:**

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>External Magnetic Field $B$, T</th>
</tr>
</thead>
<tbody>
<tr>
<td>3324-0.55mm-675C/60min-T-10mm</td>
<td>12</td>
</tr>
<tr>
<td>3324-0.55mm-675C/60min-T-20mm</td>
<td>10</td>
</tr>
<tr>
<td>3324-0.55mm-675C/60min-T-30mm</td>
<td>8</td>
</tr>
<tr>
<td>3324-0.55mm-675C/60min-T-50mm</td>
<td>6</td>
</tr>
<tr>
<td>3324-0.55mm-675C/60min-T-75mm</td>
<td>4</td>
</tr>
<tr>
<td>3324-0.55mm-675C/60min-T-100mm</td>
<td>2</td>
</tr>
<tr>
<td>3324-0.55mm-675C/60min-T-300mm</td>
<td>1</td>
</tr>
</tbody>
</table>