Development of MgB$_2$ Superconducting Coils for Nuclear Physics Applications

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And of course, our grant sponsor: DOE NP
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Outline

- Motivation of SBIR project
- Background on MgB$_2$ superconductors
  - Conductor properties
  - Applications
- Phase II efforts
  - SBIR Phase II Objectives
  - 1$^{st}$ MgB$_2$ solenoid coil
  - 2$^{nd}$ MgB$_2$ coil
  - Next steps
Motivation of project (1)

- An e-lens system is currently under construction at BNL to increase RHIC luminosity.
- It consists of room temperature copper and superconducting solenoids.
- The optimization of the system is limited by the power consumption of the room temperature solenoids (currently limited to \( \frac{1}{2} \) MW).
- The proposed MgB\(_2\) magnets can significantly increase the field to significantly improve the design and performance of the e-lens system while consuming little power.
• A RHIC luminosity upgrade was endorsed by Nuclear Science Advisory Committee (NSCA) in its report published in 2007. The e-lens project has a goal to increase luminosity and reduce loss of the circulating proton beam in RHIC with head-on beam-beam compensation.
• The size ($\sigma$ of Gaussian distribution) of the beams in the interaction region should be adjustable within range of at least (0.28 - 1.0) mm.
• An electron beam with current around 1.0 A and energy 5-10 keV will be injected in the interaction region using dipole components of tilted solenoids. The electron beam is fully confined by the axial magnetic field from the cathode of the electron gun to the entrance into the electron collector.
• To get an electron beam with $\sigma=0.8$ mm in the interaction region one needs to have the ratio of magnetic fields in the interaction region to the cathode of 2.52. The field in the interaction region should be as high as possible to provide “rigidity” of the beam. The available power allows us to have maximum magnetic field on the cathode of 8 kG, which leaves us with approximately 2 T field in the interaction region, which is barely sufficient.
Motivation of project (3)

- The available electrical and cooling power of 500 kW at the location of these e-lenses is barely enough for operation of the e-lenses in the “nominal” regime with maximum magnetic field on a cathode of the electron gun 8 kG.
- Extending the range of the electron beam radius and “rigidity” of the central magnetic field would require operating in a “maximum” regime with total power in excess of 1 MW.
- Extending the power capability to this range would take substantial capital investment and time.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gun coil (GS1)</th>
<th>Gun-transition coil (GS2)</th>
<th>Gun bending coil (GSB)</th>
<th>X-Dipole coil (GSX)</th>
<th>Y-Dipole coil (GSY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h$_{\text{cond}}$ (mm)</td>
<td>14.0</td>
<td>14.0</td>
<td>14.0</td>
<td>6.35</td>
<td>6.35</td>
</tr>
<tr>
<td>ID$_{\text{water}}$ (mm)</td>
<td>9.0</td>
<td>9.0</td>
<td>9.0</td>
<td>4.75</td>
<td>4.75</td>
</tr>
<tr>
<td>B$_{\text{insul}}$ (mm)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>Dimensions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID (mm)</td>
<td>173.48</td>
<td>234.0</td>
<td>480.0</td>
<td>178.0</td>
<td>193.0</td>
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<tr>
<td>OD (mm)</td>
<td>553.08</td>
<td>526.0</td>
<td>859.6</td>
<td>192.0</td>
<td>207.0</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>262.8</td>
<td>379.6</td>
<td>262.8</td>
<td>580.0</td>
<td>580.0</td>
</tr>
<tr>
<td>N$_{\text{layers}}$</td>
<td>13</td>
<td>10</td>
<td>13</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>N$_{\text{pancakes}}$</td>
<td>9</td>
<td>13</td>
<td>9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Nominal regime**

<table>
<thead>
<tr>
<th>M - field (B, Gauss)</th>
<th>8000.0</th>
<th>4468.0</th>
<th>3202.0</th>
<th>160.0 (5mm)</th>
<th>160.0 (5mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power P (watt)</td>
<td>58.0</td>
<td>25.6</td>
<td>45.0</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>Current I (A)</td>
<td>1188.0</td>
<td>731.0</td>
<td>769.0</td>
<td>239.0</td>
<td>258.0</td>
</tr>
<tr>
<td>Total power consumed by all magnets in 2 E-lenses (kwatt)</td>
<td>525.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Maximum regime (nominal+40%)**

<table>
<thead>
<tr>
<th>M - field (B, Gauss)</th>
<th>11200.0</th>
<th>6256.0</th>
<th>4482.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power P (watt)</td>
<td>114.0</td>
<td>50.0</td>
<td>88</td>
</tr>
<tr>
<td>Current I (A)</td>
<td>1663.0</td>
<td>1023.0</td>
<td>1077.0</td>
</tr>
<tr>
<td>Total power consumed by all magnets in 2 E-lenses (kwatt)</td>
<td>1029.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• Solenoids powered with copper coils provide the simplest and most inexpensive way to obtain axial magnetic fields.
• One option is to use solenoids with coils made with superconductors operating at ~4 K.
• Depending of field, capital cost of NbTi or Nb$_3$Sn magnets > Cu magnets.
• MgB$_2$ solenoids cooled by return (exhaust) helium gas of LTS solenoids without the need of adding new cryogenic facilities.

**Therefore 10-25K MgB$_2$ solenoids can potentially allow the full optimization of e-lens system currently limited by the availability of power to energize copper solenoids**

• Also, with MgB$_2$ magnets BNL could realize savings in operating costs (electricity), and minimize the capital costs from upgrading infrastructure (transformers, switch gear, breakers, etc.).
Superconductivity in MgB$_2$ was publicly announced in January 2001 by Japanese scientists.

Lengths currently up to 5 km @ 0.8 mm, scaling up to over 60 km.
Manufacturing capabilities

Newly Added Process Equipment for “Wind and React” and “React and Wind” coils:

• 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
• 1m+ coil winding capacity designed for strain-sensitive wire
• 6 km lengths (currently)
• Equipment in place for 60+km lengths
• Large conduction cooled coil testing available
MgB₂ strand recipe: critical current

C-doped MgB₂

$I_c$ based on 15% f.f.

4 K, 4 T:

$J_c = 200,000$ A/cm²

$I_c = 245$ A (0.83 mm)

20 K, 1 T:

$J_c = 300,000$ A/cm²

$I_c = 350$ A (1 mm)

$B_{c2}$ (4.2K) = 29.7 T

(SiC-doped wire)

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(SiC-doped wire)
MgB$_2$ superconductor applications

Superconducting Fault Current Limiter

5-20MW wind turbine

MgB$_2$ Superconducting Wire

Specialty MRI

Custom MgB$_2$ MRI magnet

DC Cables

Hyper Tech
Hyper Tech Magnesium Diboride superconductors enables liquid helium free magnets.

MRI manufacturers’ have stated MgB₂ wire is the only option in the time frame that is needed to convert to non-helium bath cooling.

$50 million industry effort to convert to MgB₂.

We are currently working with 5 MRI manufacturers.
Availability of helium

Cost of helium increasing rapidly because U.S. Strategic Reserve being depleted

Helium shortage worldwide predicted, present situation is worse than 2009 NAS report


Statement by MRI manufacturer: “We will commercialize regardless of liquid helium price increases” because:

**Safety:**
- Immune from helium vessel ruptures.
- Magnet requires no special measures to prevent helium from entering examination room.

**Cost (lower cost MRI magnet system):**
- Lower manufacturing cost due to fewer components.
- Reduced site cost: no quench infrastructure.
- No liquid helium replenishment on installation or in service if magnet quenches.
- No air shipping of magnets filled with liquid helium.

MgB$_2$ Image Guided Radiation Treatment Medical System
Advantages of MgB$_2$: 

- Reduction of size and weight of machine
- No joints in rotor pole (long length conductor)
- Faster normal zone propagation
- Meets current density requirements (< 4T)
- Made round to be easier to configure into complex coil geometries
- Significant reduction of cost
- Persistent coils

Concepts and projects using MgB$_2$: 

- Hyper Tech has designed a modular 5 MW land based direct drive wind turbine generator that is transportable, sponsored by DOE
- All cryogenic 10 MW Superconducting wind turbine rotor and stator, S. Kalsi (2014 IEEE Transactions of Applied Superconductivity 24)
- NASA 1 MW demonstrator
- Studies in Europe, including Airbus & Rolls Royce
Coil for resistive SFCL

Coil for inductive SFCL

Advantages of MgB$_2$:
- Low cost wire, much lower than HTS
- Can vary thermal conductivity by wide choice of resistive & conductive materials
- Is in a wire form that can be wound bi-filar and can be twisted and/or braided to reduce AC loss
- Is readily available in quantity and lengths
- Wire can be sized to designed current level

Conduction cooled cryostat at Ohio State University for testing both inductive and resistive SFCL coils
SBIR Phase II objectives

- **Demonstrate $[\text{MgB}_2]$ technology to the National Laboratories**
  
  - BNL will model and design larger appropriate MgB$_2$ coils for Nuclear Physics needs
  - Hyper Tech will conduct R&D to develop the fabrication techniques for these MgB$_2$ coils
  - Hyper Tech will build several MgB$_2$ coils
  - BNL will incorporate these coils into their test cryostat
  - BNL will carry out extensive life cycle testing of the MgB$_2$ coils over a large number of power, quench and thermal cycles and finally perform field quality measurements and other rigorous evaluation to confirm that coil performance and reliability is appropriate for this Nuclear Physics and other future accelerator facilities.

Modeling for MgB$_2$ solenoids (1)

Magnetic model of the basic e-lens system showing copper solenoids and a dipole coil on either side of the superconducting solenoid (right) and magnetic field in Gauss along the central trajectory (right).

Field in Tesla superimposed on the Cu coils on left and MgB$_2$ coils on right.
Field in Tesla on the axis created by MgB$_2$ coils (solid black) and copper coils (dash red) in RHIC e-lens system.
Coil #1 (based on GS1)

“Ball-park” parameters of MgB$_2$ for GS1 coil producing 1 T

<table>
<thead>
<tr>
<th>GS1 Starting Parameters</th>
<th>260000</th>
<th>260000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amp.turns</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Amp turns</td>
<td>1300</td>
<td>2600</td>
</tr>
<tr>
<td>Amp</td>
<td>0.088</td>
<td>0.088</td>
</tr>
<tr>
<td>Radial Spacing (mm), approx</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Axial spacing (mm), approx</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Joverall (A/mm$^2$)</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Length of the Solenoid (m)</td>
<td>0.263</td>
<td>0.263</td>
</tr>
<tr>
<td>Number of Layers</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Number of turns/layer</td>
<td>260</td>
<td>260</td>
</tr>
<tr>
<td>OR (m)</td>
<td>0.091</td>
<td>0.093</td>
</tr>
<tr>
<td>Average radius</td>
<td>0.089</td>
<td>0.091</td>
</tr>
<tr>
<td>Average circumference (m)</td>
<td>0.560</td>
<td>0.568</td>
</tr>
<tr>
<td>Conductor Length (m)</td>
<td>729</td>
<td>1478</td>
</tr>
<tr>
<td>Approximate Cost/m($)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Approximate Total cost ($)</td>
<td>7286</td>
<td>14777</td>
</tr>
</tbody>
</table>

Actual parameters of MgB$_2$ solenoid

- $B_0 = 0.7$ T (15 K)
- 86 A
- $J_e = 170$ A/mm$^2$ (15 K)
- $IR = 0.0876$ m
- Length of solenoid = 0.263 m
- 2180 turns
- 8 layers
- 272.5 turns/layer
- Conductor length = 1229 m
Coil #1 fabrication

On winding machine

After epoxy impregnation
Coil #1 – characterization at OSU

Coil dewar internal assembly

Coil instrumentation schematic
Coil #1 – characterization results

HyperTech/OSU/BNL MgB$_2$ Coil for eRHIC

$I_c$ @ 0.1 $\mu$V/cm in 2$^{nd}$ Layer

Brookhaven successfully measured coil, closely matching OSU’s results
Coil #2 ("react and wind")

18” demonstration conductively-cooled “React and Wind” coil

- $I_c = 152$ A (20 K)
- $J_e = 275$ A/mm² (20 K)
- $B_w = 0.83$ T (20 K)
- $B_0 = 0.15$ T (20 K)
- Coil ID = 0.46 m (18”)
- Coil height = 20 mm
- 225 turns
- 12 layers
- 19 turns/layer
- Conductor length = 406 m
- Conductor $\phi = 0.84$ mm
Coil #2 – characterization results

Technology developed for “React and Wind” large coils: smooth transition terminations, controlled tension coil winding, epoxy impregnation, cool down, and testing.

As instrumented in cryostat at OSU

Coil load line shows that coil out-performed short sample at 15K, 20K and 30K!
Next steps

• Life time cycle tests will be performed on the R&W MgB$_2$ coil (#2) at BNL:
  - Power up and down cycle to 90% of the short sample
  - Thermal cycles
  - Over-current cycle hitting quench detection threshold. It is important to learn that the model coils developed in the Phase II are robust enough to handle quenches non-destructively.
  - Quench propagation and other related studies

• 3rd coil based on GS coil
  - React and wind technology vs. W & R
  - Conduction cooled
  - Longer conductor piece length, i.e., 1500 – 2000 meters
Thank you!