Space Research Experiments with Bulk Superconductors

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Support and cooperation with the Deutsche Luft- und Raumfahrt (DLR), Cologne and Airbus, Bremen, Germany, and ISAS of Japan Aerospace Exploration Agency (JAXA), Japan greatly acknowledged.
Special thanks to Volker Schmid, Detlef Konigorsi, Ingo Rühlich, and Tomotake Matsumura
HTS production >1 ton precursors

- powder, targets (55%)
  Y, Dy, Gd, Sm, BZO

- sintered components (5%)
  high density, max. 92%

- REBCO bulks (40%)
  single, multi-seed, melt textured

2nd generation CC
- high in-field $I_c$
- mech. strength
- low AC loss

- thin film

L~27 500 km!
- 4 mm; 1 µm

HTS bulks
- high $J_c$
- trapped field $B$
- mech. strength
- robust
- long term stab.

HS devices
- HTS bearings
- mobile cryostats
- motor elements
- space application

Align of research strategy to those of industrial partners!
HTS bulk materials in space application

YBCO bulk → YBCO back

Comparison & analysis

MFX

Trapped field pattern → Magnetic excitation
YBCO bulk scanning experiments

BEFORE

Av 75.11  Max 462

Av 76.49  Max 453

AFTER

Av 110.8  Max 702

Av 110.5  Max 693
Earth Magnetosphere – screens the solar wind

The Earth's magnetic field shields the Earth's surface from the direct impact of the solar wind (or of a comet's poisonous tail).

Ref. J. Hoffman, MIT 2005
Earth magnetic field interacts with bulk HTS

Screening /attenuation effect of the earth magnetic field

Flux compression (transient)

Shielding $B_{\text{earth}}$ by bulk HTS

(D 270 mm x H 7 mm)
Proton irradiation tests (2x10 kRAD)

Before

After
Hall probe scanning and proton irradiation of melt textured YBCO bulk

<table>
<thead>
<tr>
<th>Sample</th>
<th>YBCO</th>
<th>1. measurements</th>
<th>2. measurements</th>
<th>Change B av %</th>
<th>Change B max %</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-seed</td>
<td>Z14-8</td>
<td>425 / 832</td>
<td>401 / 791</td>
<td>402 / 814</td>
<td>-5.6 %, -5.4 %</td>
</tr>
<tr>
<td></td>
<td>original</td>
<td>No irradiation</td>
<td>No irradiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 - seed</td>
<td>Z 14 - 2</td>
<td>444 / 903</td>
<td>427 / 841</td>
<td>423 / 846</td>
<td>-3.8 %, -4.7 %</td>
</tr>
<tr>
<td></td>
<td>original</td>
<td>10 kRAD Prot.</td>
<td>10 +10 kRAD</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Relative change:

Proton beam tested samples:

\[
\Delta B_{\text{max}} = -6.75\% \text{ (10 kRAD)} \\
\Delta B_{\text{av}} = -3.75\% \text{ (10 kRAD)}
\]

Untested samples; non-irrad.

\[
\Delta B_{\text{max}} = -4.80\% \\
\Delta B_{\text{av}} = -3.55\%
\]

Conclusion:

After 10 kRAD + 10 kRAD proton irradiation no changes in the trapped field measurements could be detected!

Hence, it is assumed that the performance of HTS bulk devices in space application due to proton impact shows no degradation in the critical current density and in the structure of the magnetic domains.
Space application: MAGVECTOR
Interaction between Earth magnetic field and variable (super)conductor
Protection Shielding

Radiation has long been recognized as one of the most serious health problems facing astronauts exploring space beyond the Earth’s magnetic shield.

The Mars rover Curiosity mission has allowed to calculate the averaged radiation to 1.84 mS/day which is for a 180-day journey an exposure of more than 8 times higher than the radiation limit for a worker in a nuclear power plant in the same time.

Protection a cylindrical habitable volume **2.5 m diameter, 3.5 m length** with enough aluminium to absorb protons with kinetic energies less than $E_g$ is given by

$$M(\text{kg}) = E_k(\text{MeV})^{1.67}$$

To stop protons with energies less than 1.2 GeV **requires 139 tons** of shielding material.

The mass of magnetic systems would be **one or two orders of magnitude** less than the mass of an equivalent aluminum shield.
MFX (Magnetic Field Experiment); funded by DLR e.V. and BMFT

Moving electrical conductor and sensors through Earth’s magnetic field. Measurement of the field conditions of the ram and wake side of the conductor. ISS is a perfect lab for this measurement. Set up and initial operation phase by ESA astronaut Alexander Gerst. Intention to continue scientific campaign until 2016.
International Space Station (ISS)
MFX/ MagVector Experiment

Stirling Kompressor
Cold head
Water cooling
3D Helmholtz coil
Vacuum cryostat

Interaction
ISS flight direction
Ram side
Wake side
B_{Earth}
HTS

Installation ISS
ISIS Drawer, ~ 75 kg

Alexander Gerst

MFX/ MagVector cryostat

Interaction
ISS flight direction
Ram side
Wake side
B_{Earth}
HTS

Installation ISS
ISIS Drawer, ~ 75 kg

Alexander Gerst
HTS block (mass 800 g) cool-down curves
Stirling cryo-cooler AIM 400 (3.5 W)

Improved vacuum
$6 \times 10^{-5}$ mbar

HTS $T_c = 91$ K

Shut-down cooler
90 min

Cooling down MFX
MHD / Magnetic pressure consideration: Re-entry magnetic heat shield

\[ \frac{\partial}{\partial t} (v \rho) = F - \frac{\partial}{\partial x} \left( \frac{B^2}{2\mu_0} \right) \]

Superconductors can shrink the size and weight of the magnet considerably, and possibly provide extremely large focusing fields.

\[ J \times B = - \nabla \left( \frac{B^2}{2\mu_0} \right) + \left( B^* \nabla \right) B / \mu_0 \]

Lorentz force consists of magnetic pressure force and magnetic tension force.
Conclusion

• Bulk high-Tc superconductor is becoming a prominent material in space application
• Magnetic shielding and thermal induced flux compression capability is demonstrated
• 20 kRAD proton bombardment on YBCO bulk in a cyclotron revealed no significant changes.
• MFX/MAGVECTOR experiment at the ISS since 2014 give insights into ways how magnetic fields influence electrical conductors
• MFX will continue with new mission „Horizons“ in 2018