The US National 2212 Program


Thanks to many people who contributed slides – LBNL, MetaMateria, nGimat, OST, SMS, TAMU, U-CO, UW-EC


Supported by NSF-DMR core grant, DOE-High Energy Physics (HEP), NIH, and State of Florida
Drivers for the 2212 program – magnets that generate > 30 T – NMR and DOE-HEP machines

2212 research and development at US companies, national labs, and universities

- Powder – new sources for powder - nGimat and MetaMateria
- Wire – variety of architectures, filament count, wire diameter, twisting, swaging - OST
- Insulation – has to survive heat treatment - NHMFL and nGimat
- Processing – overpressure processing– NHMFL, LBNL
- Strengthening 2212 wire – apply strong laminate - SMS
- Characterize processed wire – NHMFL, LBNL, U-Colorado, UW-Eau Claire
- Characterize coils – NHMFL, LBNL
- Basic research – NHMFL, LBNL, TAMU, NCSU
NHMFL NMR demonstration coil
“Platypus” – 2212 Magnet

- 2212 NMR demonstration magnet
- Generate high field and field homogeneity - towards > 30 T NMRs
- Central solenoid plus pair of compensation coils to correct $z^2$ term

- ~7.1 T (Bi-2212) + 16.4 T LTS
- 240 mm high
- 92 mm OD
- 44 mm ID
- 0.7 km of 1.3 mm dia. wire
- 179 turns
- 18 layers
Two companies now making 2212 powder in US

- Nexans was the sole source of 2212 powder until 2015 when they quit making powder
- Two US companies now make powder – research and development funded by Dept. of Energy (DOE-HEP)
  - MetaMateria
  - nGimat
- Reproduce 2212 composition made by Nexans
- 2212 powder from both companies have reasonable $J_c$ performance
Develop reliable starting powder for Bi-2212/Ag wire and become a powder supplier

Key Powder Characteristics - identified by MetaMateria

- High 2212 phase purity
- Low trace impurities – (Fe, Zn, Cr, Al)
- C and H < 100 ppm
- Low secondary phases (< 1% 2201, CuO, AEC)
- Tap density > 1.5 g/cc
- Melting point tolerance ± 2 °C
- Minimal hard particles > 10 μm in size
Powder Preparation

Precursor

Heat Treatment

Grinding

Post Treatment

A few hard particles

Sengupta
nGimat - Use spray combustion to form 2212 powder
nGiConductor™ Bi2212 powder production

- Post-processing furnace equipment capable of...
- Current throughput capabilities for finished products...
- "Bottom-up" approach: *No milling or grinding*
$J_C$ of wires - Nexans, MetaMateri, nGimat

nGimat powder close to Nexans performance

![Graph showing $J_C(4.2K)$ versus Applied field (T)]
Wire production

- Oxford Superconducting Technology (OST)
- Commercially available 2212 round wire
Can vary the 2212 wire architecture: 2212 filaments and bundles, wire diameter, aspect ratio, swaging, twist pitch
2015 Developments

- Scaled up billets from 2 kg to 10 kg.
- Improved density through swaging, increasing $J_E$.
- Moving from Nexans to new powder vendors.

*Baseline Nexans 2 kg Billet*
2015 Densification by Swaging Developments

Projected Benefits:
1. Reduce coil volume changes
2. Reduce OP req. for high $J_E$
3. Continuous Process

<table>
<thead>
<tr>
<th>Density Change from Swaging</th>
<th>As Drawn</th>
<th>After Swage</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire</td>
<td>8.88 g/cc</td>
<td>9.21 g/cc</td>
<td>3.7%</td>
</tr>
<tr>
<td>2212*</td>
<td>4.75 g/cc</td>
<td>5.93 g/cc</td>
<td>25%</td>
</tr>
</tbody>
</table>

*Assumes constant FF
Compare to CIP and OP

- Smoother Surface
- Merged filaments reduced
- Reel to reel process under development

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<table>
<thead>
<tr>
<th></th>
<th>MetaMateria</th>
<th>nGimat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Architecture</td>
<td>1.2 mm, 85 fil. x 18 bundles</td>
<td></td>
</tr>
<tr>
<td>Best $J_E$ (15 T, 1 m)</td>
<td>326 A/mm$^2$</td>
<td>257 A/mm$^2$</td>
</tr>
<tr>
<td>Avg. $J_E$</td>
<td>234 A/mm$^2$</td>
<td>257 A/mm$^2$</td>
</tr>
<tr>
<td>Best OP (5 T) $I_c$</td>
<td>900 A</td>
<td>1000 A</td>
</tr>
<tr>
<td>Hard Particles</td>
<td>Some</td>
<td>None</td>
</tr>
</tbody>
</table>

- Both suppliers have delivered 1+ kg batches.
- Development is ongoing collaboratively (ASC & Vendors):
  - nGimat: Composition, phase purity.
Insulation – must withstand 900 °C heat treatment for wind-and-react coils and insulate at 4.2 K

• Alumino-silicate braid – thick and reacts with 2212
• Develop dip-coat TiO$_2$ – based insulation
  – NHMFL
  – nGimat
TiO$_2$ insulation – developed at NHMFL and nGimat – mixture of TiO$_2$ particles and organic chemicals

Insulation developed by NHMFL

Kandel, McGuire, Lu

Insulation developed by nGimat

- 1 – 2 µm thickness control
- Excellent concentricity
- Uniform thickness over length of wire

White
Fabricating wind-and-react coils

• NHMFL - solenoid coils for NMR demonstration projects – single strand

• LBNL
  – Subscale race track coils made with 17-strand Rutherford cable
  – CCT coil – single strand

• OST/OI – interest in building demonstration solenoid coils – single strand
Fabricating coils

NMR demonstration solenoid coil wound at NHMFL

Subscale race track coil at LBNL

Led by Trociewitz

Courtesy of Arno Godeke
Overpressure (OP) processing 2212 coils

- OP processing removes current-limiting bubbles in 2212 filaments
- OP furnace capabilities at NHMFL and LBNL
  - LBNL – OP furnace operated up to 50 atm
  - NHMFL – 4 OP furnaces ranging from 25 to 100 atm total pressure
    - Smaller OP furnaces for wires and small coils
    - Large Deltech furnace
      - Available to international 2212 community
      - Currently have coils/samples from NHMFL, LBNL, RIKEN, CERN
OP furnace capabilities - NHMFL

100 atm OP furnace – used for research

Deltech 50 atm furnace – cold wall system
Strengthening 2212 strand

• Strengthening being developed by Solid Materials Solutions (SMS) (talk by Otto)
• Method to strengthen individual strand
  – Diffusion bond laminate on slightly-aspected 2212 wire
  – Wind coil
  – OP heat treat coil
Mechanical properties of plain and strengthened wires

$I_c$ degradation of 5% is at $\varepsilon_{\text{irr-5\%}} = 0.60\%$ ($\sigma = 160$ MPa)

Tested at 77 K
OP-HTed Wire: pmm130723-2, 37x18, 0.8 mm


Strengthened wire made by Alex Otto at ASC and SMS

(0.4%, 425 MPa)
Characterization of processed wire/cable

- NHMFL – Boebinger talk on sheath hardness
- LBNL – Shen talk on strain/quench studies
- UW-Eau Claire and U-Colorado – collaborate to study $I_c$–strain relations and degradation mechanisms
Normalized $I_c/\text{strain}$ behavior and microstructure

1 atm vs. 100 atm OP overview

100 atm OP – compression – cracks and buckling across groups of grains

$T = 4.1$ K
$B = 16$ T
$E_c = 0.1 \mu$V/cm

Cheggour

Jewell
Characterize and demonstrate coils/cables

- NHMFL – NMR solenoids
  - Electromagnetic, microstructural, high-field capabilities
  - NMR demonstration coils
    - Internal NMR program
    - RIKEN

- LBNL – high-energy physics machines
  - Subscale race track coils
  - CCT coils
Demonstration projects

NHMFL NMR Project
“Platypus”

LBNL subscale race track coils

LBNL CCT coils
2212 Research

- NHMFL - grain connectivity, optimizing OP processing
- LBNL – strain/quench studies, thermal processing
- TAMU – new thermal processing
- NCSU – work with SBIR partners
Textured-Powder Bi-2212/Ag Wire – avoid 2212 melting

- Mix 2212 powder + Ag powder
- Uniaxial pressing forms bar with aligned 2212
- Fabricate PIT wire
- Heat treat just below $T_{\text{melt}}$ (2212) to prevent melting

7 filament wire
7x19 wire

Not successful yet
Quench/strain studies, heat treatment studies - Shen

Quench studies on various conductor architectures

Heat treatment studies

Shen
Texture studies

Strong, local biaxial texture in 2212 filaments

Kametani
OP processing Design of Experiment study – investigate importance of and interaction between four parameters
Summary – US 2212 program

• Focused on developing coils to demonstrate that 2212 can be used for high-field magnets
• US effort is spread among several groups – companies, national lab, and universities
• There are research and development efforts in all major areas needed for 2212 coils