Magnets for materials and materials for magnets
Credit due

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Magnetic materials are inherently quantum mechanical, strongly correlated, and complex. (Good enough for a physicist)
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The physical properties that emerge from this complexity can actually be quite useful. (Magneto-resistive, Magneto-caloric, Magneto-strictive, ...)

Spin-off technology from pure research in magnetism has had significant and wide-ranging impact. (NMR, SQUID)
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Magnetism is intricately related to superconductivity, and particularly important in the highest temperature superconductors. Unconventional superconductors can have spectacular magnetic properties.
Magnetic fields

“Applied magnetic field is a versatile, contact-free knob that can be used to tune the properties of materials.”
“Quantum oscillations” of transport properties under applied magnetic field can map the Fermi surface of a metal.

Extract subtle materials information without strongly altering the system.

“Applied magnetic field is a versatile, contact-free knob that can be used to tune the properties of materials.”
Magnetic fields - Examples

Applied magnetic field can induce new phases of matter which don’t exist under zero-field conditions. (Bose-condensed triplons, vortex matter, etc.)

Strongly alter the ground state of a material. (Quantum phase transitions)

Magnetic fields - Examples

Applied magnetic field can induce dramatic changes in the non-magnetic properties of a material.

Giant+Magneto+X = Useful.

“Applied magnetic field is a versatile, contact-free knob that can be used to tune the properties of materials.”
Magnetic fields - Generation

(1) Permanent Magnets

Pros: Simple, cost-efficient, stable
Cons: Relatively low field, no field variability

“All magnets are good magnets.”
Magnetic fields - Generation

(2) Solenoids

Pros: On-demand, variable fields, any size and geometry.

Cons: Cost scales quickly with field. Coil heating.

“All magnets are good magnets.”
(3) Superconducting (Persistent Current) Magnets

Pros: High fields, precise field selection

Cons: Cost, cryogenics, complexity, size

“All magnets are good magnets.”
These options are “materials limited”.

- Permanent magnets limited by moment size, density, anisotropy
- Electromagnets limited by resistive heating and structural integrity of conductor.
- Persistent superconducting magnets are limited by critical current density and low critical temperatures.

Unfortunately, these are “mature” limitations.

“All magnets are good magnets.”
Magnetic fields - Generation

For some applications, none of these solutions are appropriate anyway.

In my case, I want to study materials response to magnetic fields with x-rays. So, I need:

- Optical access
- Small volumes
- Precise tunable field strength, variable temperature
- Very high magnetic fields

No standard solution. So, try non-standard solutions. Hope for less mature limitations.

“All magnets are good magnets.”
Mini-Coil Pulsed Magnets

The idea: Tiny resistive magnets, short pulses of current

- Trade energy for energy density
- Generate very high instantaneous fields
- Keep time-integrated current (heating) low
- Measure time-resolved effects

Pioneered by H. Nojiri, now in use at SPRing-8, Advanced Photon Source, ESRF, SNS, ILL, ...
Mini-Coil Pulsed Magnets

Critical materials: Cu-Ag nanocomposite wire
Mini-Coil Pulsed Magnets


Generates millisecond-long pulsed magnetic fields, up to 30 Tesla. Rep rate is ~3 times per hour.
Mini-Coil Pulsed Magnets

Generates millisecond-long pulsed magnetic fields, up to 30 Tesla. Rep rate is ~3 times per hour.


\[ C \sim 1.8mF \]
\[ R \sim 0.1\Omega \]
\[ L \sim 0.1mH \]
Mini-Coil Pulsed Magnets


Generates millisecond-long pulsed magnetic fields, up to 30 Tesla. Rep rate is ~3 times per hour.
Can we justify that duty cycle? Consider the alternatives.
Florida Bitter Magnet: “The most powerful resistive magnet on earth”

<table>
<thead>
<tr>
<th>Strength</th>
<th>36.2 tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Resistive</td>
</tr>
<tr>
<td>Bore size</td>
<td>32 mm (~1.25 inches)</td>
</tr>
<tr>
<td>Online since</td>
<td>December 2005</td>
</tr>
<tr>
<td>Cost</td>
<td>$0.5 million</td>
</tr>
<tr>
<td>Weight</td>
<td>2,500 kg (2.75 tons)</td>
</tr>
<tr>
<td>Height</td>
<td>1.52 meters (~5 feet)</td>
</tr>
<tr>
<td>Water used per second</td>
<td>139 liters (~37 gallons)</td>
</tr>
<tr>
<td>Power required</td>
<td>19.6 MW</td>
</tr>
</tbody>
</table>
Florida Bitter Magnet: “The most powerful resistive magnet on earth”
Tohoku Mini-Coil: “The most economical resistive magnet on earth”? 
Compensate low duty cycle by collecting data efficiently.
Array of fast-framing integrating detector strips capture a two-theta arc as a function of time (field).


Collect full field dependence (and hysteresis) in a millisecond!
Is this thing actually useful?
Susceptibility anisotropy in iron arsenide superconductors


Susceptibility anisotropy in iron arsenide superconductors

- Anisotropy has been widely discussed in terms of “electronic nematicity”

- Various theories of the iron arsenides involve “spin-nematic” transitions or orbital order.

Fang/Kivelson - PRB 77, 224509 (2008)
Xu/Sachdev - PRB 78, 020501(R) (2008)
Chen/Devereaux - PRB 82, 100504(R) (2010)
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Susceptibility anisotropy in iron arsenide superconductors

- Within the orthorhombic phase, crystals are twinned.

- Anisotropy is clear from the SDW order (collinear AFM stacking along a-axis)

- Anisotropy in thermodynamic measurements is masked by twinning.
Susceptibility anisotropy in iron arsenide superconductors

![Graph showing orthorhombic strain as a function of temperature](image)

- Orthorhombic (H,2,0) direction
- Tetragonal (0,K,0) direction

![Diagram showing direction of applied magnetic field and x-ray momentum transfer](image)
Suppose that: $\chi_a \neq \chi_b$

Then, the free energies of the two twin volumes will differ in applied magnetic field.

- Twin planes will move.
- Volume fractions will change.
- Bragg peak intensities will change.
Direction of applied magnetic field
Direction of x-ray momentum transfer
(H,0,0)
(0,K,0)

Tet
Tet

χa < χb
Increasing Time

Temperature (K)

Applied Magnetic Field (Tesla)

Suppression of (B // a) domains

100 %

0 %
Now for something completely different...
Trapped Flux Magnets

The idea: Superconductor - Permanent Magnet Mash
TRAPPED FLUX IN SUPERCONDUCTORS

By A. B. PIPPARD

The Royal Society Mond Laboratory, Cambridge

(Communicated by D. Shoenberg, F.R.S—Received 16 November 1954)

Figure 20. Flux lines at end of normal channel. The superconducting regions are shaded; the broken curve shows the direction of a reverse field aiding migration.
Trapped Flux Magnets

1989 - 0.6 Tesla demonstrated

1995 - 10 Tesla “achievable”
Trapped Flux Magnets

High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 tesla at 29 K

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† Railway Technical Research Institute, 2-8-38 Hikari-cho, Kokubunji-shi, Tokyo 185-8540, Japan

Large-grain high-temperature superconductors of the form RE-Ba-Cu-O (where RE is a rare-earth element) can trap magnetic fields of several tesla at low temperatures, and so can be used for permanent magnet applications. The magnitude of the trapped field is proportional to the critical current density and the volume of the superconductor. Various potential engineering applications for such magnets have emerged, and some have already been commercialized. However, the range of applications is limited by poor mechanical stability and low...
Trapped Flux Magnets

Future promise of TFMs is great. But - we can make use of them now.
Trapped Flux Magnets

Tunable field and optical access
Trapped Flux Magnets

Metamagnetic phases of TbNi$_2$Ge$_2$
Magnetic field generation is a critical component for the study of materials.

Simultaneously, magnetic field generation is itself a materials-limited problem.

A “Virtuous Circle” of discovery can arise when scientists study materials for magnets, as well as study materials with magnets.
Further reading


