# Conductor for MRI magnets beyond NbTi

'*Conductors for commercial MRI magnets beyond NbTi: requirements and challenges*', SuST 30 (2017) 014007


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College of Engineering

**Imagination at work**

MT-25
30 August, 2017

# Content

- Commercial MRI market
- MRI magnet design
- Conductor requirements
- Alternative conductor options

# Can $MgB_2$ / HTS substitute NbTi?

## Potential of $MgB_2$ / HTS

- No-liquid cryogenics
  - Reduced installation and life-cycle cost
  - Serviceability
- Very stable: <almost> no quench

## Challenges

- Conductor cost
- Is conductor performance adequate in volume production?
- Is it  a drop-in conductor? Does it require re-development of the magnet technology?
- Is it a drop-in magnet? Is there MRI system interference?

# MRI Market: Large and Growing

- Superconducting MRI: >75% of the installed base
  - Annual production: about 4,000 SC scanners
  - New installations
    - >90%: whole-body 1.5T (75% total) and 3T (25%) cylindrical scanners
    - <10%: Specialty and 7T+ scanners
    - About equal: “standard patient bore” 60 cm and “wide bore” 70 cm diameter units

- Customer demands
  - Better image quality, faster scanning
  - Lower installation and service cost
    - Price of the installed commercial scanner must be below $3M (3T)

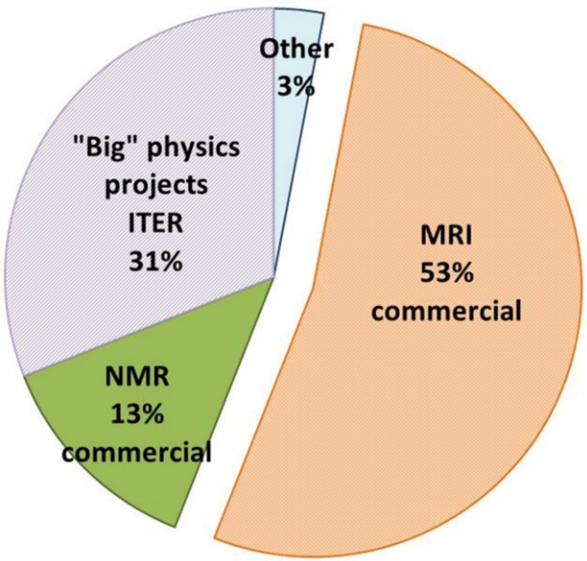

GE Discovery 750w


Philips Ingenia


Siemens Skyra

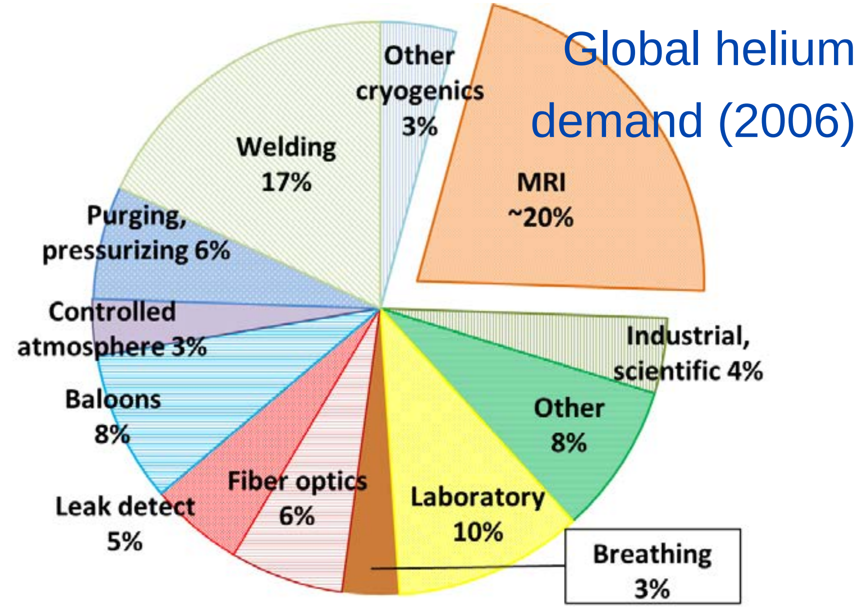
# Largest Application of Superconductivity

MRI industry uses about 70% of all NbTi conductor




- Annual use: 3,000 to 5,000 tons/yr
- Meets all MRI conductor needs
- Long lengths, guaranteed, predictable performance, mechanically strong, manufacturing friendly
- Price: ~$1/kAmp/m @ 4K, 4 T

MRI is the largest user of helium




- NbTi challenge: He refrigeration
- MRI use ~20% of all helium
  - 1990s: only 5%

Commercial MRI market

Superconducting MRI magnets

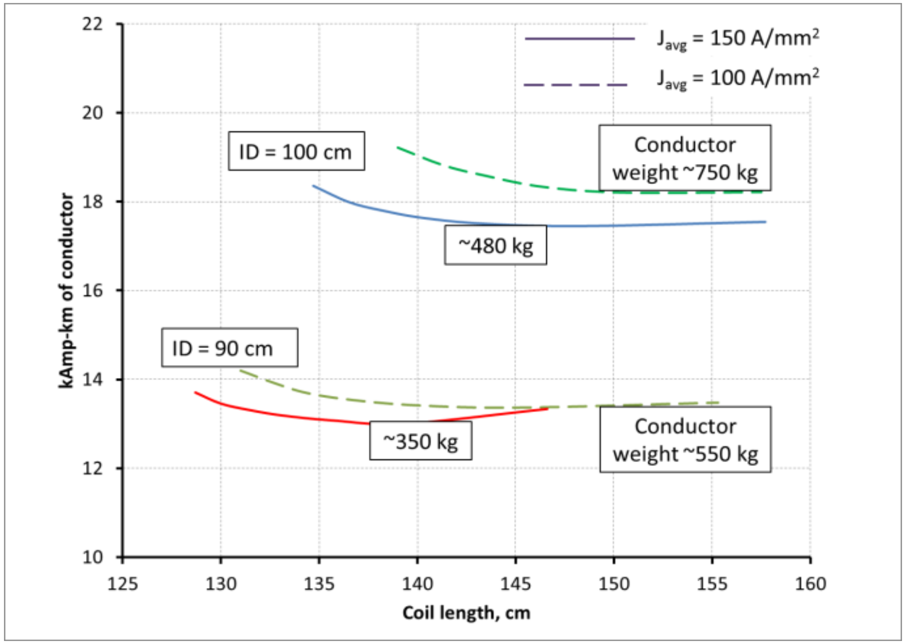
Specify conductor

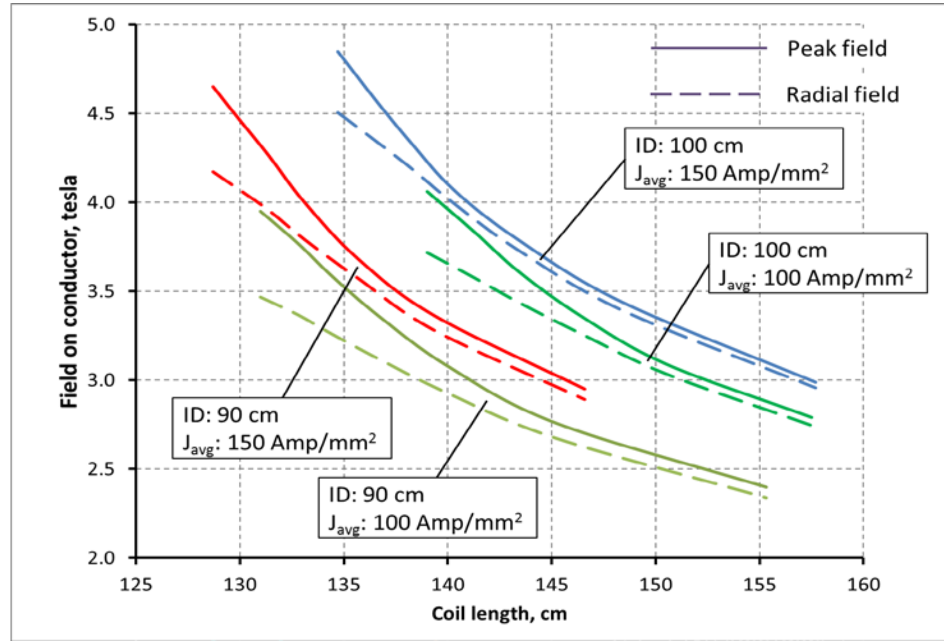
Future projects

# Whole-body NbTi MRI magnets

| | 1.5 tesla | 3 tesla |
|---|---|---|
| Length, cm | 125-170 | 160-180 |
| Patient bore | 60 cm (std bore) and 70 cm (wide bore) | |
| Outer diameter, cm | 180-210 | 180-210 |
| Uniformity, 10 ppm peak-to-peak in ellipsoid | • 30 cm to 45 cm axial direction<br>• 45 cm to 55 cm in radial direction | |
| 5-gauss line (Z x R), m | 4 x 2.5 | 5 x 3 |
| Field decay | <0.1% field loss a year | |
| Liquid helium | Up to 1,500 liters | |
| **Derived parameters** | | |
| Stored energy, MJ | 2 - 4 | 8 - 15 |
| Peak field, T | 3 - 6 | 5 – 6.5 |
| Amp-Length, kA-km | 15 - 25 | 35 - 60 |
| Conductor weight, kg | 400 - 800 | 1,000 – 3,000 |

# Design details – 1.5T example




- NbTi-based coil technology: conductor parameters are within a narrow range optimized for the lowest cost for given performance
  - Conductor length (Amp-m), peak field, energy, mechanical properties
- $MgB_2$ / HTS may require different magnet configuration that will increase the system cost
  - Partly driven by different cooling options

MRI marketplace

Superconducting MRI magnets

Specify conductor

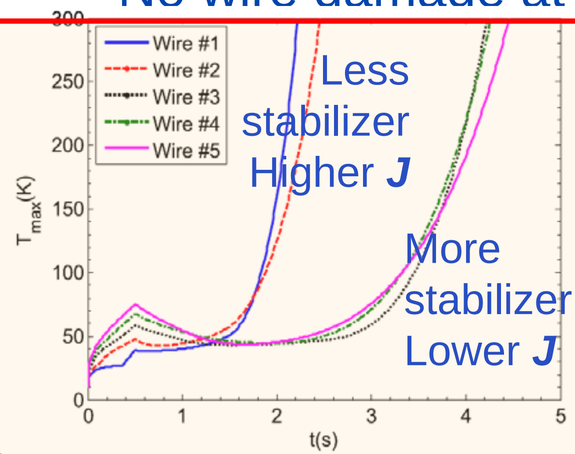
- Field generator
- Uniformity
- Persistence
- Insulation
- Manufacturability

Conductor Specification

Alternatives

# Field generator

- 15 kAmp-km of conductor per 1.5 T magnet
  - Operating current: 300 Amp minimum ➔ up to 50 km of wire per magnet
- $J_{avg}$: 120 Amp/mm$^2$ or higher
- Field on conductor: 3.5 T or higher
- Mechanical properties
  - No degradation under production or operation stress
- Consistent with quench protection
  - Can not be damaged during quench
  - No wire damage at full current for time $t_o$ ~$10^5$ $A^2$-sec/mm$^4$ /$J^2$




| ***J***, Amp/mm$^2$ | 100 | 200 |
|---|---|---|
| $t_o$, sec | ~10 | ~2.5 |

Ch. Poole, et al - "*Numerical study on the quench propagation in a 1.5 T $MgB_2$ MRI magnet design with varied wire compositions*", SUST, **29**, pp. 044003 (2016)

# Field uniformity

## High, predictable, non-variable spatial uniformity

- Multi-coil configuration
  - High radial field
  - High compression stresses
- Tight dimensional tolerances
- No magnetic materials in conductor (target)
- Even, predictable current distribution in superconductor / filaments
- Uniformity shall not change over time
  - Screening currents shall not affect uniformity (NMR experience)
  - Shall not screen superconducting shims (if used)

➔ **Multifilament, twisted wire –** not tape

# Persistence

- Average field decay: <0.1 ppm/hr (<0.1% field loss a year)
  ➔ Total voltage drop in the circuit shall be
  - 1.5 T: <0.2 micro-volt at 1,000 Amp
  - 3T: <1 micro-volt
- SC joints: R < $10^{-12}$ ohm at 0.5 tesla field
  - Joints to wire and to switch
- N > 25 @ 3 tesla: guaranteed over 100% length
  - N = 40: can operate at up to 70% ***Ic***
  - N = 25: ~45% ***Ic*** to meet persistence Spec
- No filament breaks and sausaging
  - Develop inspection methods (eddy current?)
- No field shift due to eddy currents induced by gradient coils
- ?? Thermal switch if operate at 10K or above – new technology

Trade-off: driven magnet
- Reduced image quality
- High cost of a dedicated high-stability power supply
- Losses in charging leads

# Manufacturability (commercial magnets)

- No / minimum conductor inspection / test before winding
  - Guaranteed properties over 100% length
- Strongly preferred: no coil reaction / heat treat after winding
- Long lengths: most pieces shall be >3 km, 1 km minimum piece length
- Precision wind
- Fast winding in production environment
- Yield: >90% of conductor shall be in deliverable magnets (target)
  - Low breakage rate, minimum scrap, no failure in magnets
- Sourcing: same form-fit-function wire available from several vendors

# Conductor Spec for commercial MRI

| Property | Requirements |
|---|---|
| Conductor shape | Round or rectangular wire (not cable or tape) |
| Filaments | Multi-filamentary, twisted (~100 mm pitch) |
| Critical current | >500 Amp @ operating temperature $T_{op}$, 3 T |
| $J_{c\_eng}$, Amp/mm$^2$ | >250 Amp/mm$^2$ @ $T_{op}$, 3T including insulation |
| N-value | >25 guaranteed over 100% length |
| Yield strength @ Rp=0.2% | >100 MPa |
| Bend radius | <50 mm |
| Processing | No processing / heat treat after winding |
| Quench protection | Carry full current for time $10^5$ Amp$^2$mm$^{-4}$ / Jeng$^2$ without overheating above 100℃, no damage |
| Insulation | Continuous (braid or varnish). BDV > 1,000 V |
| Dimensional tolerances | Less than ±10 micron |
| Conductor length (layer-wound) | 20-30 km per magnet<br>70%: more than 3 km; Min usable length: 1 km |

# Conductor alternatives

- OK (green)
- So-so (blue)
- Show-stopper (red)

| Strand | $MgB_2$ in-situ | $MgB_2$ ex-situ | Bi:2212 | Bi:2223 | YBCO | $Nb_3Sn$ |
|---|---|---|---|---|---|---|
| Selected Manufacturers | HyperTech | Columbus | OST | Sumitomo | SuperPower | HyperTech |
| Shape (wire / tape) | Wire | Wire | Round wire | Tape | Tape | Wire |
| Filament, µm | 40 | 60 | 200 | 200 | 4000 | 30 |
| Twist, mm | 20 | ? | 80 | ? | none | 20 |
| Std bare dia / cross-sect, mm | 1.2 | 3 x 0.5 | 1.2 | 4.3 x 0.23 | 4.0 x 0.1 | 0.5 |
| $I_c$, @ std dia (4K, 3.5 T) | 500 | 300 | 600 | 520 | 400 | 650 |
| $J_{e,w}$ (4K, 3.5 T), A/mm$^2$ | 385 | 125 | 530 | 425 | 850 (⊥) | 2870 |
| Persistent joints? | Y | Y | N | N | N | Y |
| Yield Strength, MPa | 200 | 120 | 120-150 | 130 | 550 | |
| Min Bend R, mm (W&R) | (16) | (easy) | NA | ? | (easy) | (10) |
| R&W | 150 | 62.5 | 100 | 80 | 11 | 62.5 |
| Protection time, sec As is | Very short | -- | 0.35 | 0.55 | 0.13 | 0.012 |
| (With added stabilizer, $J_{eng}$ = 250 A/mm$^2$) | (2.4 sec) | | (3.2) | (2.7) | (5.5) | (8) |
| Magnetic materials used? | Yes, 100 mT | Yes | None | None | None | None |
| Wind-and-react | W&R | NA | W&R | NA | NA | W&R |
| React-and-wind | R&W | R&W | R&W | R&W | R&W | R&W |
| Insulation | Tape | Tape | Tape | Tape | Tape | Braid |
| Piece length, km | 3 | >1 | 1 | 1.5 | ? | 5 |
| | Development | Too far | Too far | No | No | Cost |

# Conclusion

- HTS / $MgB_2$ conductor is not ready for use in <u>commercial</u> MRI
  - NbTi remains the conductor of choice
  - In-situ $MgB_2$ is the closest option but still behind NbTi
- When HTS / $MgB_2$ may be called “good enough” for <u>commercial</u> MRI:
  - Meets all performance requirements
  - Price <$2/kAmp_m @ 4K, 3T (NbTi: ~$1/kAmp-m)
  - Annual production: >100 tons
  - Available from multiple vendors
- Conductor: significant development
  - Conductor specific for MRI: high Ic and Jc, multifilament, guaranteed properties, …
  - Improved quench characteristics (both wire – and magnet technology)
  - Insulation compatible with manufacturing and refrigeration
  - Reliable, predictable long-length production
- Magnet technology development
  - Optimized refrigeration
  - Quench protection
  - Joints
  - Switch (if above 4K)
  - Manufacturing technology
  - System issues
  - And more

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CONSIDERATIONS IN THE DESIGN OF MRI MAGNETS WITH REDUCED STRAY FIELDS

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Abstract

One of the major considerations in siting choice for an MRI system within a hospital is its interactions with its environment. This interaction places restrictions on the proximity of equipment sensitive to magnetic field and limits areas of general public access. In addition special account must be taken of the possible impact of environmental iron on magnet homogeneity. To date, the approach adopted by the MRI system scanner manufacturers to these problems has been to employ either YOKE or MIRROR iron (PASSIVE) shielding frequently requiring significant structural modifications with associated costs. An alternative approach to the shielding problem has been investigated at OXFORD using a geometry utilising superconducting counter running coils alone and prototypes with central fields of 0.5T, 1.0T and 1.5T have been tested.

Introduction

Since 1982, over 500 superconducting magnets of field strengths 0.5 Tesla - 2 Tesla have been installed at Magnetic Resonance Imaging (MRI) facilities Worldwide, and it is anticipated that by 1990 this number will have risen to at least 2000.

Although it has not been a limiting factor in the growth of the MRI market to date, due in part perhaps to early installations occurring at research or premium hospital sites, the stray field matures and purchases by smaller and 'downtown' hospitals become more commonplace, that these stray field installation problems will become more acute.

In light of the stray field siting difficulties considerable effort has been expended by the MRI system manufacturers towards solving this problem, and two solutions, Room Shielding and Yoke Shielding have achieved widescale commercial application in reducing the stray field profile of the MRI magnet. In Room Shielding iron plates are placed in specific locations on the walls of the room in which the magnet is located, so as to provide limited screening of selected areas. In Yoke Shielding, iron is placed symmetrically around the magnet cryostat so as to contain the magnet flux locally. In this paper, the relative advantages and disadvantages of these two approaches are compared with that of a third approach 'Active Shielding'. An Actively Shielded system is one which employs superconducting coils to cancel the field at distances remote from the magnet origin. The technological difficulties in the design of such a system are discussed.

The Oxford Program on Magnet Shielding

Starting in 1982, a continuous program of work has been undertaken at OXFORD aimed at developing solutions to the magnet shielding problem. In 1983 software was developed based on an integral equation solution which was used to design passive iron Yoke