Superconducting Magnets for MRI

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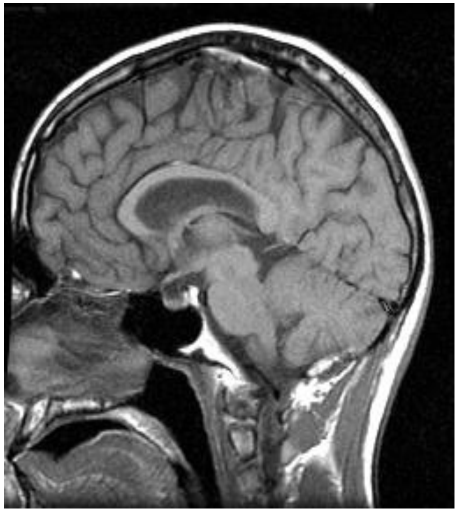
imagination at work

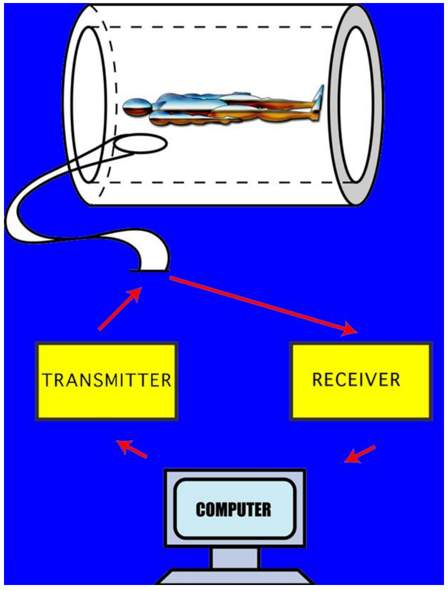
Agenda

- Introduction:
  - What is MRI
  - MRI market
  - Types of MRI magnets: field, shape, purpose
- Requirements to MRI magnet
- Electromagnetic design
- Structural design
- Cryogenic system
- Conductor
- Conclusion. Q&A

What is MRI?

- A non-invasive medial imaging to provide high quality images of the inside of patient body.
- Based on the principles of Nuclear Magnetic Resonance (NMR), especially the NMR signal of hydrogen nuclei.
- Strong magnetic field and gradient field are required to polarize and encode the frequency of MR signals.
- Radiofrequency transmitter and receiver coils are used to initiate and measure the MR signals for imaging.



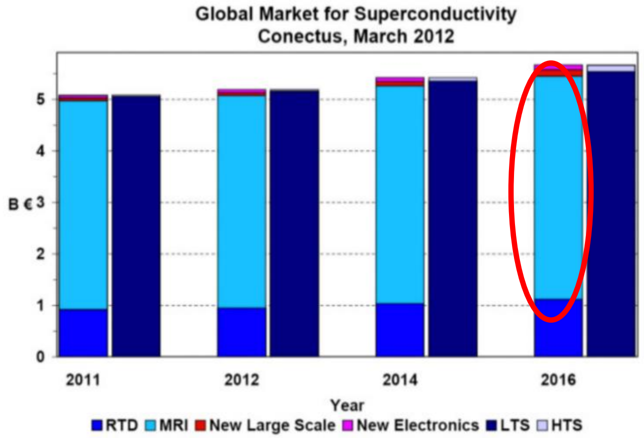


Source: www.geheathcare.com

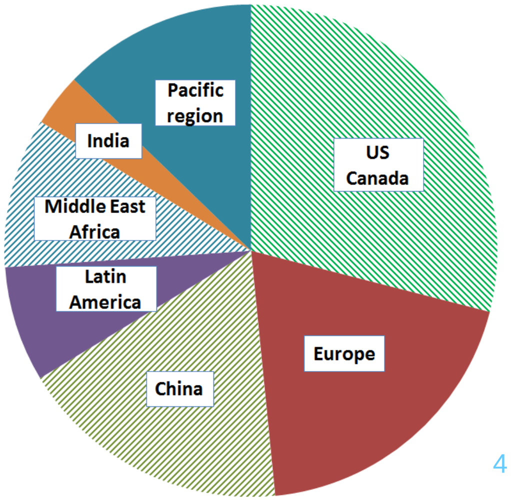
MRI Market: Large and Growing

More than 55,000 MRI units of different types are installed worldwide

- Annual production: about 4,000 scanners
- About 80 million MRI exams per year worldwide
- Superconducting MRI: >75% of the installed base
- USA and Japan: about one MRI scanner per 30,000 population
- Increasing MRI sales in developing countries including superconducting scanners
- **MRI: the largest application of Superconductivity and Helium!**



MRI market
(2015 estimate)



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Presentation to the School of Superconductivity
held in Mexico, Nov. 13, 2021

Superconducting-magnet MRI

Examples of 3 tesla wide-bore systems

GE SIGNA Premier

Philips Ingenia

Siemens Skyra

Advantages

- High image quality
- Short scan time, high throughput
- Well-controlled stray magnetic field
- Competitive life-cycle cost

Disadvantages

- High purchase / installation cost
- Expensive service contracts
- Requires liquid helium for refrigeration
- May quench: need in helium refill

More than 90% are whole-body scanners (75% 1.5T, 25% 3T)

Types of MRI magnets - Shape

Cylindrical magnets: >95% of superconducting scanners

GE SIGNA Premier 3T

Mobile MRI

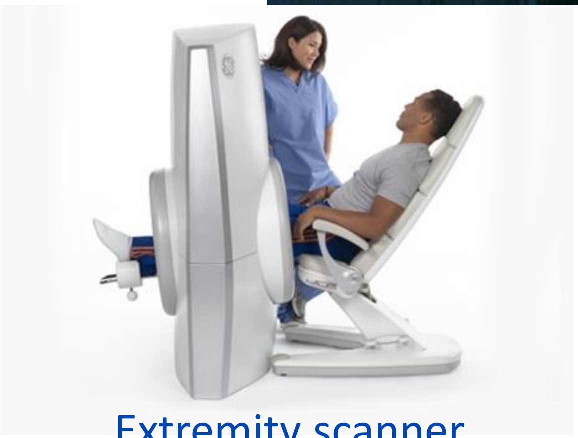
Open magnet

1 tesla Panorama (Philips)

0.7 tesla Signa (GE)

MRT:
MRI in
operating room

0.5 T Signa SP
(GE, 1995)



Extremity scanner
GE Optima 430s

Types of superconducting MRI – Field strength

- **Low Field cylindrical magnets (1.0 tesla or less)**
  - Insufficient image quality
  - Insufficient price advantage
  - 2005: Production stopped

	1980s	1990s	2000s	2010s	2020s
> 3 tesla	Do not exist	Do not exist	**Ultra-high field**	**Ultra-high field**	**Ultra-high field**
3 tesla	Do not exist	**Ultra-high field**	**High-field**	**Standard**	**Standard**
1.5 tesla	**High-field**	**High-field**	**Standard**	**Standard**	**Standard**
1.0 tesla	**High-field**	**Standard**	Production stopped	Not produced	Not produced
0.5 tesla	**Standard**	Low field	Production stopped	Not produced	Not produced

- **Higher-field commercial magnets**
  - 1.5 T and 3 T whole-body magnets constitute more than 95% of superconducting MRI magnets
  - 1.5 T is the best compromise between cost and performance
  - 3 tesla magnets: about 25% market
- **Ultra-high field**
  - 7 tesla to 11.7 tesla magnets
  - Limited to few research clinics, about 70 units installed worldwide

Agenda

- Introduction
- Requirements to MRI magnet
  - Safety
  - Patient comfort and compactness
  - Uniformity
  - Persistence
  - Stray field
- Electromagnetic design
- Structural design
- Cryogenic system
- Conductor
  - LTS
  - MgB_2 and HTS
- Conclusion

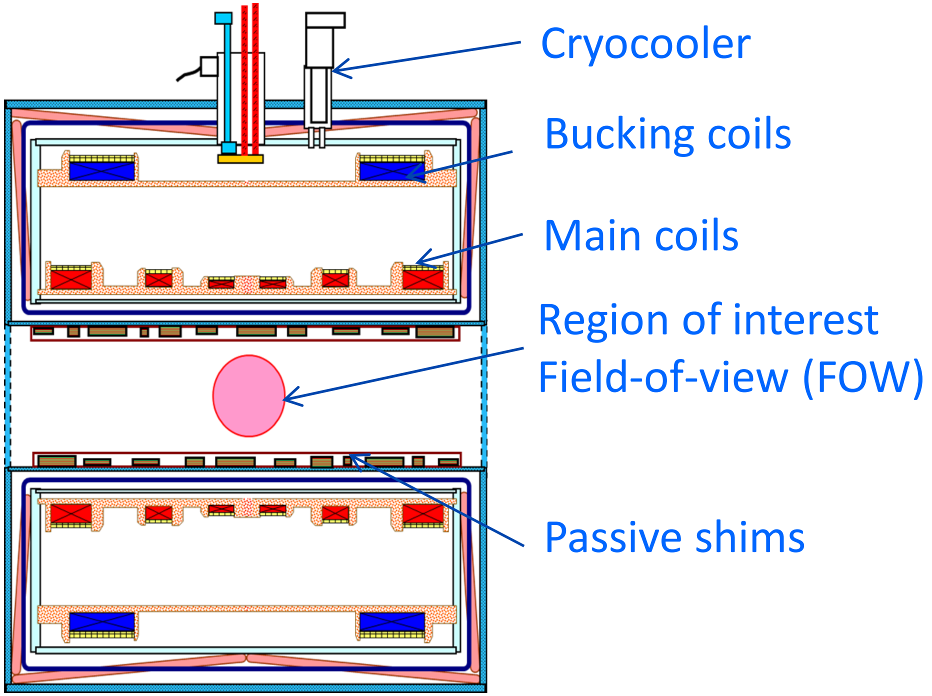
Requirements to MRI magnets

- Image Quality →
  - Magnetic field strength (1.5 tesla or higher)
  - Field uniformity in large volume (45-50 cm)
  - Field stability
- Total cost of ownership →
  - Low initial cost
  - Low operational costs (He and kWh)
- Installation & service →
  - Light weight, compact size, smaller footprint
  - Fast installation/adjustment
  - Service at field
- Further customer needs →
  - Safety (5 ga line, standards)
  - Reliable (maximum uptime)
  - High throughput (maximize revenues)
  - Compact/Accessible
  - Patient friendly (wide/open)

Commercial magnet design is always a trade-off

Field uniformity and stability

- Design Uniformity: 10 parts-per-million (ppm) in 45~50 cm diameter volume
  - Multiple-coil configuration
- Field decay:
  - Short-term decay: 1 ppb during sequence (EMI, vibration)
  - Long-term decay: less than 0.1 ppm/hour on average, less than 0.1% per year



Shielding

- Magnetic field outside of the scanning suite shall be less than 5 gauss (industry standard)
- Types of shielding
  - **Active shielding**: Use superconducting coils of opposite direction. Cost-effective, light weight – standard in commercial MRI
  - **Passive shielding**
    - Iron attached to cryostat
    - Wall shielding
- Typical 5-gauss line
  - Measured from the magnet center
  - 1.5 T magnets: ~2.5 m X 4 m (R X Z)
  - 3 T magnets: ~3 m X 5 m

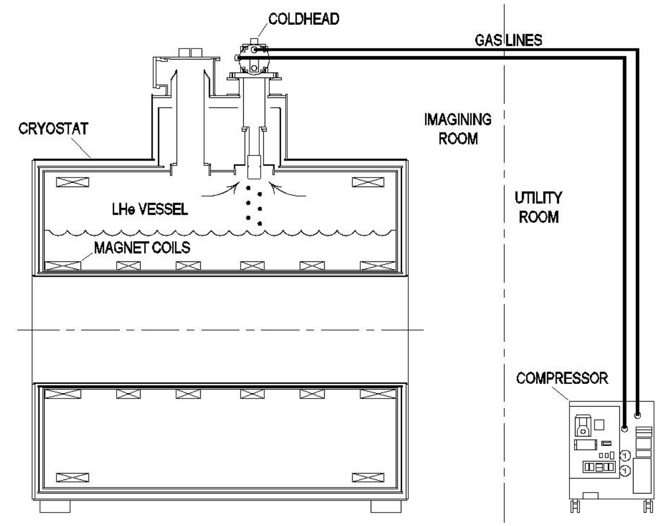
Refrigeration

- In 2000s, zero-boil-off (ZBO), or better, ***zero-helium loss*** refrigeration became standard in commercial MRI
- ZBO technology uses cryocooler to re-condense helium gas inside the cryostat ➔ No need in helium refill
- Elimination of one thermal shield, more compact magnet design
- Disadvantages of ZBO:
  - Higher refrigeration cost
  - Higher power consumption

Progress in MRI refrigeration technology

	1980s	1990s	2000-10s
Technology	Nitrogen shield	GM cryocooler	ZBO
LHe boil off, cc/hr	0.4	0.1 → 0.03	Zero
LHe refill period	4 months	1 year → 4 years	Typically, no refill
LN refill period	1-2 weeks	Not used	Not used

Principal schematic of ZBO refrigeration



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  - Coil configurations
  - Persistence
  - Quench protection
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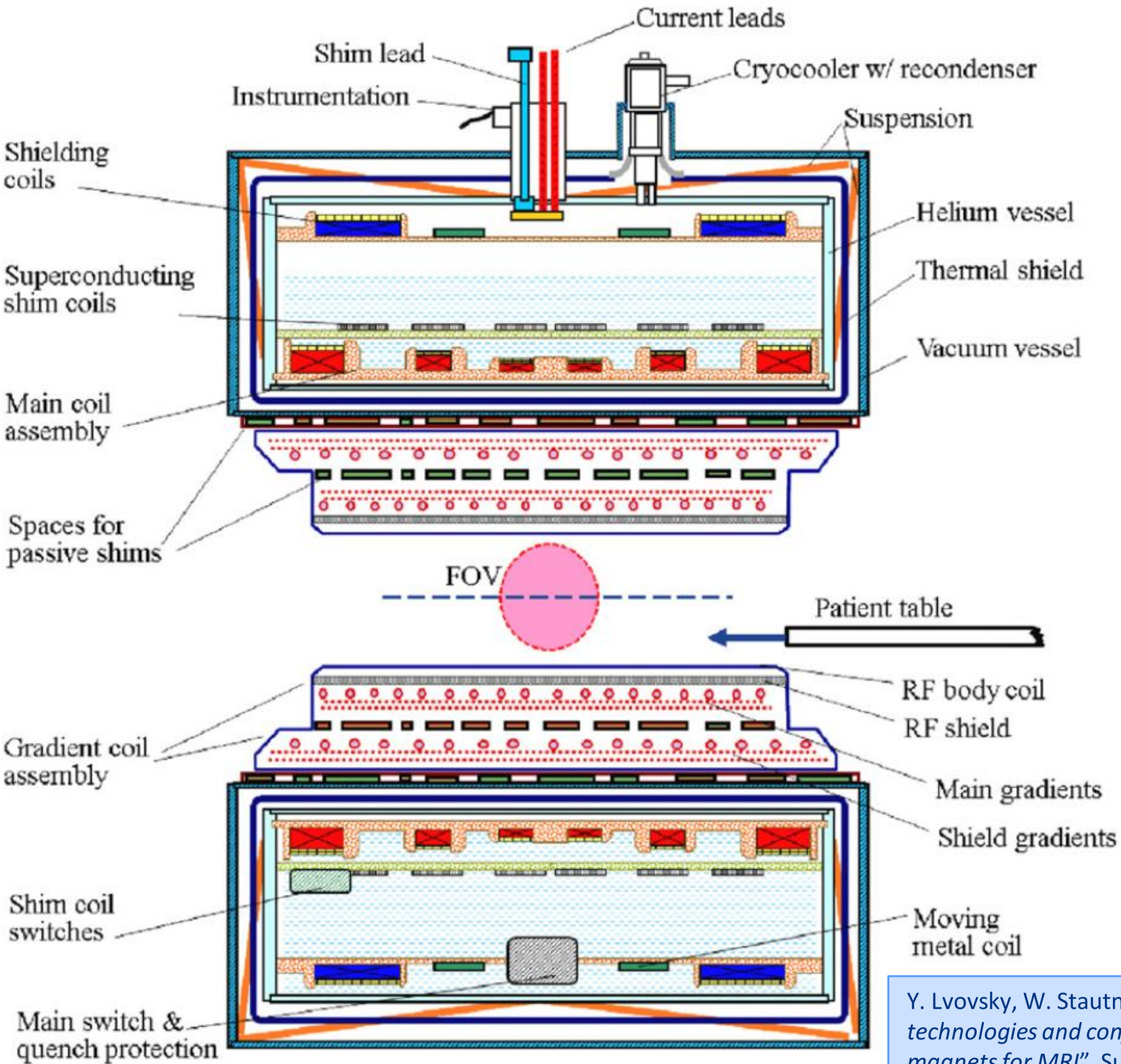
Components of MRI magnet

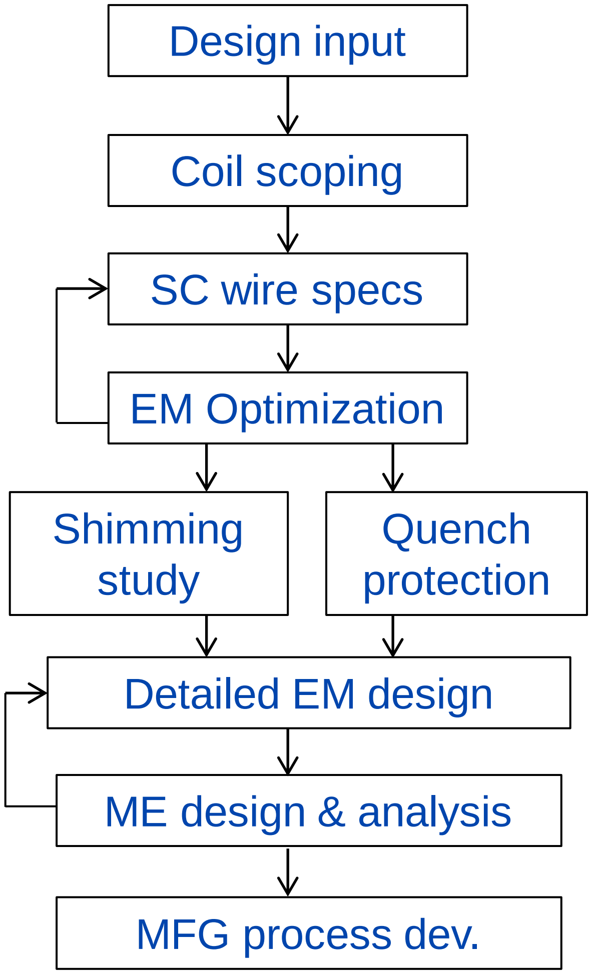


Y. Lvovsky, W. Stautner and T. Wang - "*Novel technologies and configurations of superconducting magnets for MRI*", Superconductor Science and Technology, **26** p. 1-71 (2013)

Unique in Superconducting MRI Magnets

- High field homogeneity
  - Multi-coil configuration
  - Precise coil positions
- Persistent operation
  - Superconducting joints
  - Superconducting switch
  - Passive quench protection, target no external discharge
- Minimized stray field
  - Shielding coils with reversed polarity
- Reliable operation at customer sites (hospitals)
- Price-driven: installation and life cycle

High-level Magnet Design Process



B0 field, fringe field, field homogeneity, magnet size & cost

Number of coils, wire-specs, coil peak field, operating current, magnet stack-up & coil envelope

Ic (B), wire size, insulation type, filament, RRR, piece length

Define coils size, turns/layers, spacing, Io/Ic ratio

Quench protection analysis
Field sensitivity analysis and shimming design study

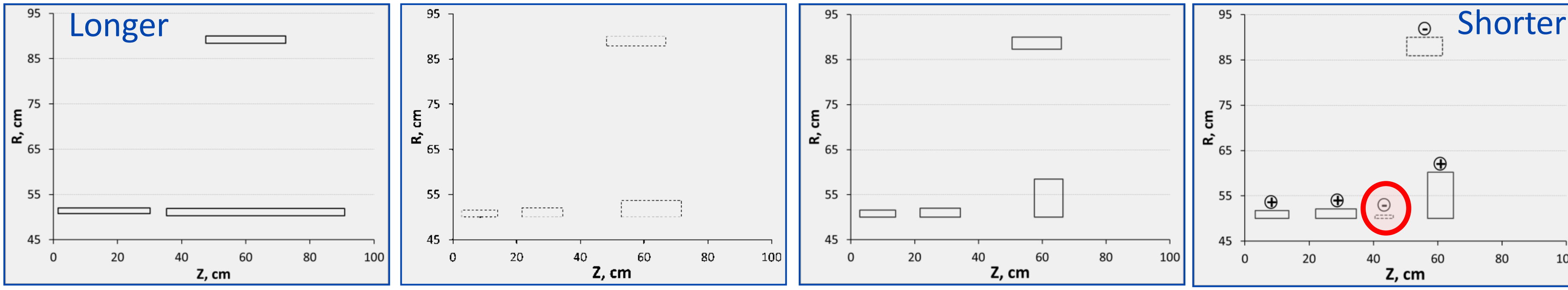
Updated coil geometry/layout, field drift calculation, moving metal compensation circuit, leads/switch design, coil cold-to-warm dimensions.

Coil and former stress analysis, thermal analysis, cryostat design

Coil/former assembly process, leads/switch/joint processes, instrumentation, test plan

From long to short magnets

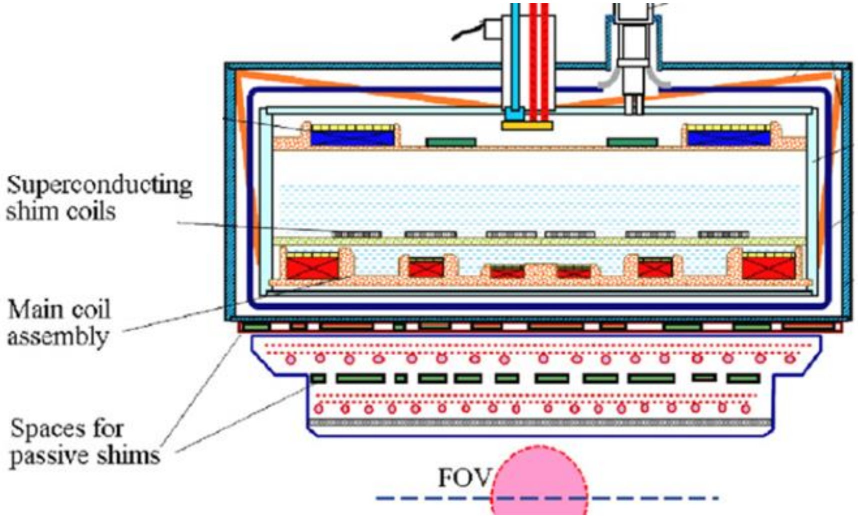
standard multi-coil configuration for 1.5 T magnets



Length	180 cm	145 cm	133 cm	130 cm
FOV	33 cm	45 cm	45 cm	45 cm
# coils	6	8	8	10
Bp	2.3	3.8	5.1	5.4
kAmp-km	4.8	4.6	4.8	5.3

- Assumption: All magnets have the same IR and OR, same current, conductor and stray field – all typical for 1.5 T magnets
- Multi-coil configuration
  - Six-coil design: can not deliver uniformity
  - Short magnets: stray field
- Conductor volume is within +/-10% for the whole range of lengths
  … but its price depends on Bp and increases for short magnets

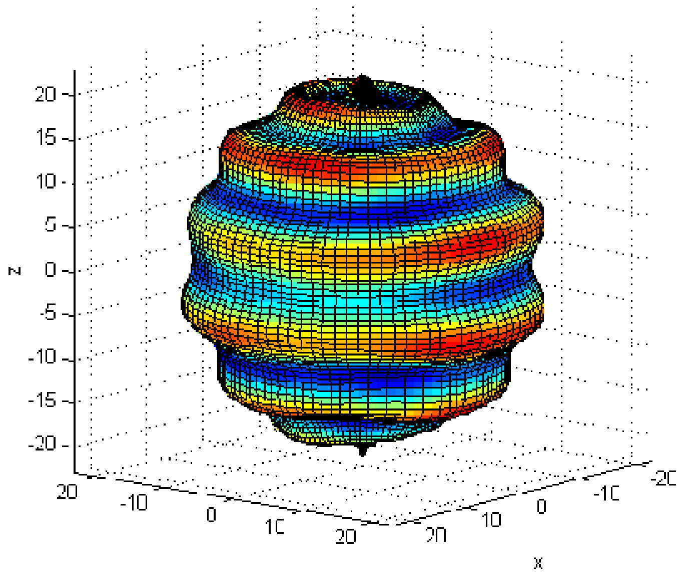
Shimming



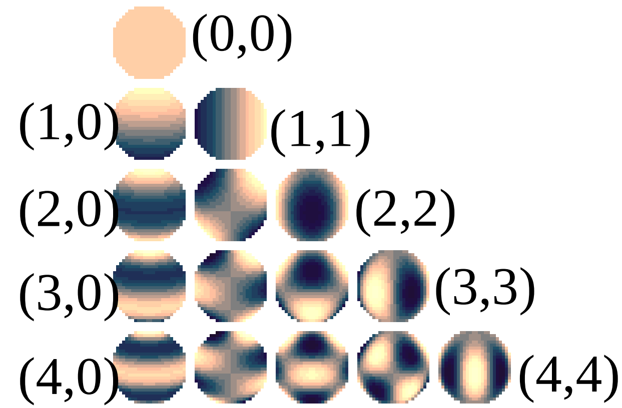
Improve uniformity from 500~1000 ppm in magnet as-built to 10 ppm

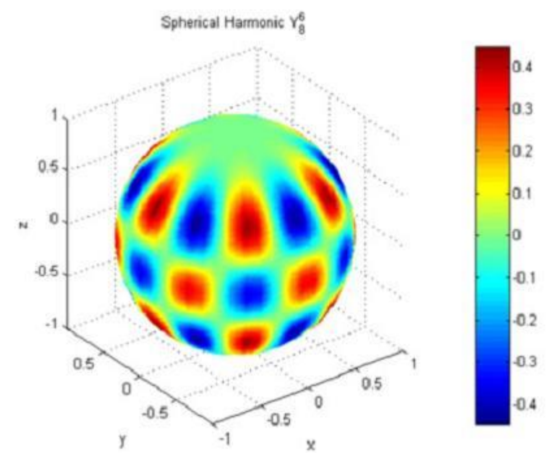
- **Passive shimming**
  - Precisely-positioned pieces of iron in the warm bore. Improves overall uniformity (not individual harmonics)
  - Lowest cost option
  - Cons: Temperature drift
- **Active superconducting shimming**.
  - Adjustable. Trade off convenience vs performance.
  - Cons: Higher cost. Interactions with magnet
- **Resistive shims** to improve uniformity in a sweet spot
  - Compensates effects of human body. Adjustable for individual patients
  - Cons: Low strength. Time-consuming shimming. Interactions with magnet.

Spherical Harmonics



Actual magnetic field distribution on a sphere can be decomposed into a set of orthogonal spherical harmonics

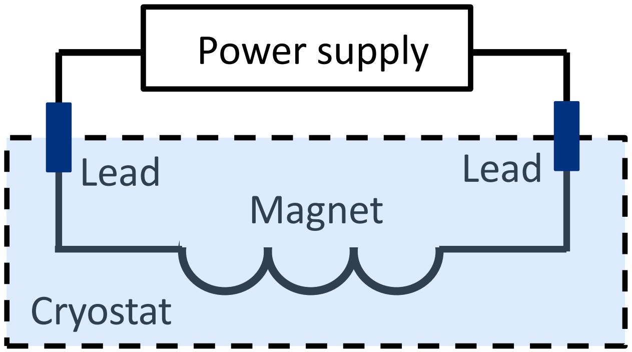




Shimming is achieved by compensating different B field harmonics by shimming coils or passive iron shims.

Field Stability

Driven magnet

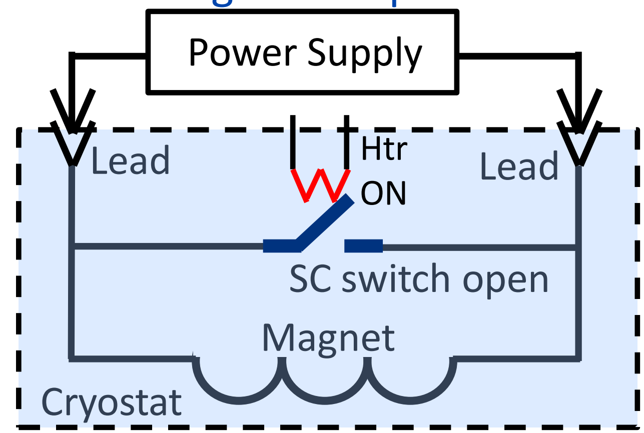


Options:

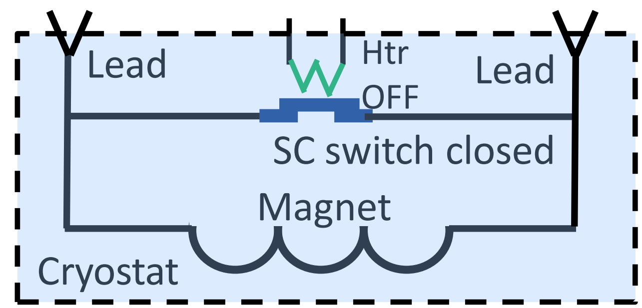
1. Driven operation
    - Expensive driver, permanently installed
    - Lead losses
2. Persistent operation: average decay <0.1 ppm/hr
    - Typical MRI/NMR configuration
    - Lower cost. Better performance
    - Requires very low circuit resistance
    - Retractable leads
    - Risk: unstable SC components

Persistent magnet

Magnet ramp mode



Persistent mode



Persistent Magnet Operation

$$B = B0\left(1 - e^{-\frac{tR}{L}}\right)$$
$$L = 2E/I^2$$
$$\mathrm{Decay} = \left(1 - e^{-\frac{3600RI^2}{2E}}\right)$$

$$\mathrm{R} < \frac{2\ Decay * E}{3600 * I^2}$$

Decay in ppm/hr

E is stored energy [MJ]

I is magnet current [A]

L is magnet inductance [A]

R is magnet resistance [ohm]

Max circuit resistance

Typical parameters for 1.5 T whole-body MRI magnets

- Decay = 0.1 ppm/hr
- *E* = 3 MJ
- *I* = 500 Amp

➔

Total circuit:

R_c < 7E-10 ohm

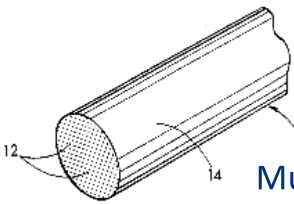
Field decay mechanisms:

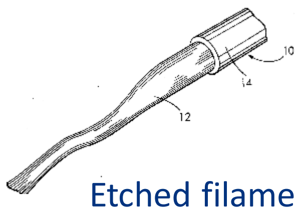
- Resistance of joints
- Decay in conductor

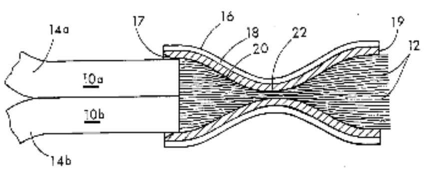
Superconducting Joints

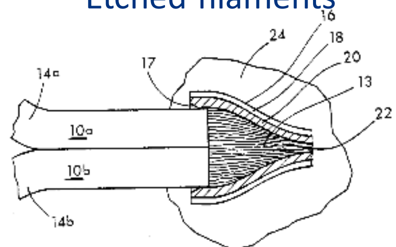
Challenges (NbTi joints)

- Target resistance $<10^{-11}$ ohm per joint, lower for low-current magnets
- Even distribution of current in filaments
- Testing in production environment
- Minimize field on joints


Multifilament conductor

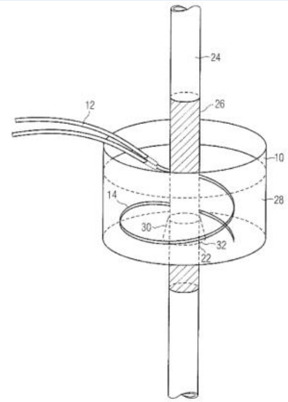

Etched filaments

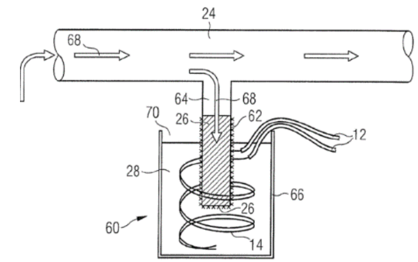

Crimp filaments


Fill with solder

US Pat. 4,894,906 (Yuchi Huang, 1990)

- Matrix etched off
- No twisting
- Filaments inserted in bimetallic tube
- Superconductor on ID of tube
- Tube crimped, filled with solder



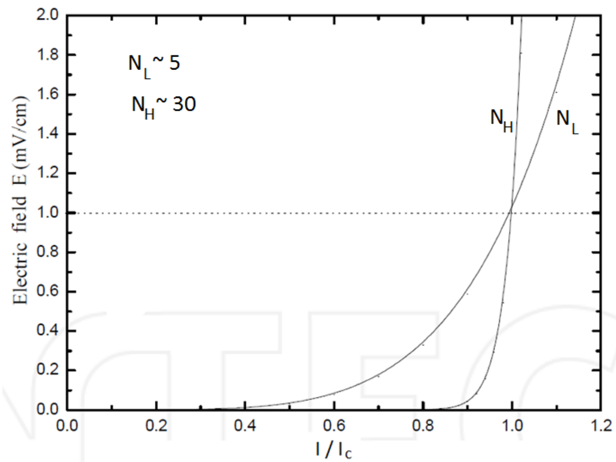


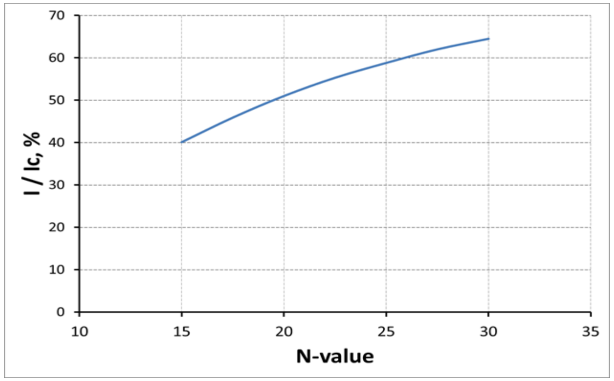
US Pat. 8,315,680
(Le Feuvre & Simpkins, Siemens, 2012)

- For use in non-helium bath magnet
- Matrix material etched off
- Filaments twisted
- Wrapped around an insulated, cryogen tube
- Placed in cup with Wood's metal

Conductor Resistance

I – V curve (best fit) $V/V_c = (I/I_c)^N$





50% reduction of N-value: need to reduce I/Ic by 30%

Typical *N*-values

- Stable and predictable in LTS
- HTS:
  - Depend on field and orientation
  - Manufacturing method
  - Significant variability

Material	N-value
NbTi	~50 @ 4 tesla >40 @ <7 tesla >30 above 7 tesla
MgB_2	~30 at zero field ~20 above 0.5 tesla
HTS	~30 at zero field ~20 above 0.4 tesla

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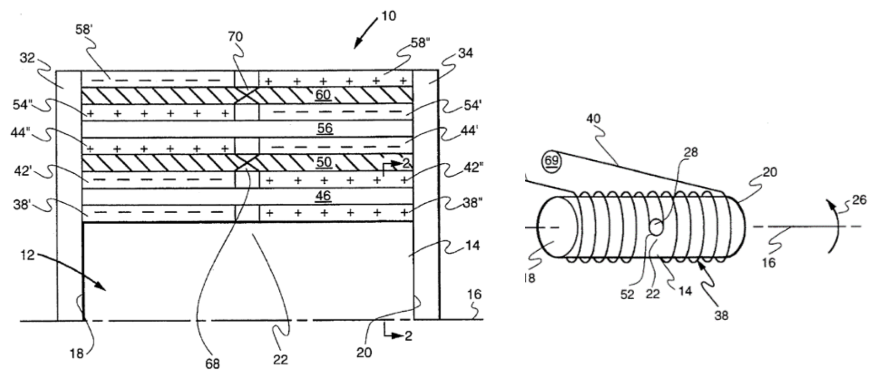
Superconducting Switch

Design Requirements

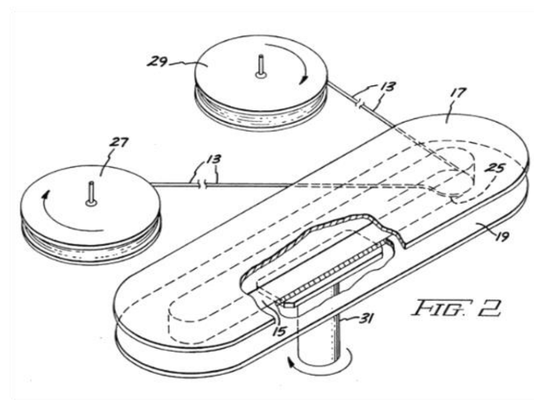
- Maximize switch resistance and minimize joule heating

$$Q = {V^2}/{R_s}\ t$$

- Minimize inductance
- Fast ON-OFF and OFF-ON transitions
- No spontaneous quenches
- High-current operation



US Pat. 5,649,353 (L. Salasoo et al, 1997)



US Pat. 5,093,645 (B.Dorri et al, GE, 1992)

- Switch for conduction-cooled magnet
- Bifilar-winding, epoxy-impregnated

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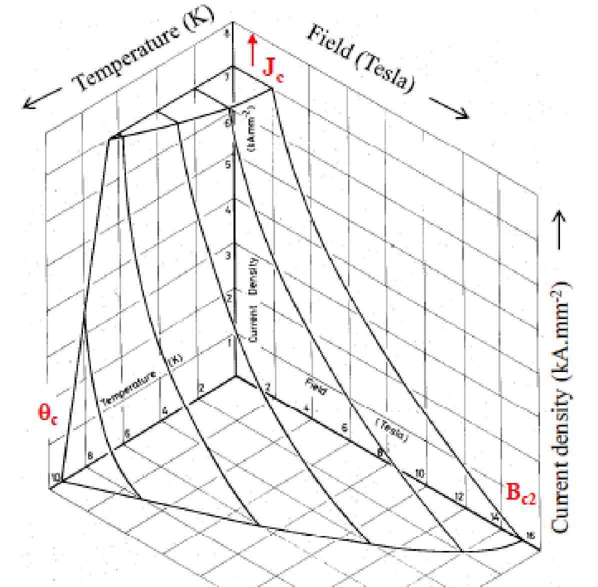
Quench Protection



NbTi critical surface

What is quench?

Superconductor becomes resistive when it exceeds the (B, J, T) critical surface.

Consequence of a quench

- Out of MRI operation, down-time
- Loss of helium
- Risks of over-heating, over-voltage, over-stress
- Risk to magnet structures
- Stray magnetic field blooming
- Field homogeneity/re-shimming

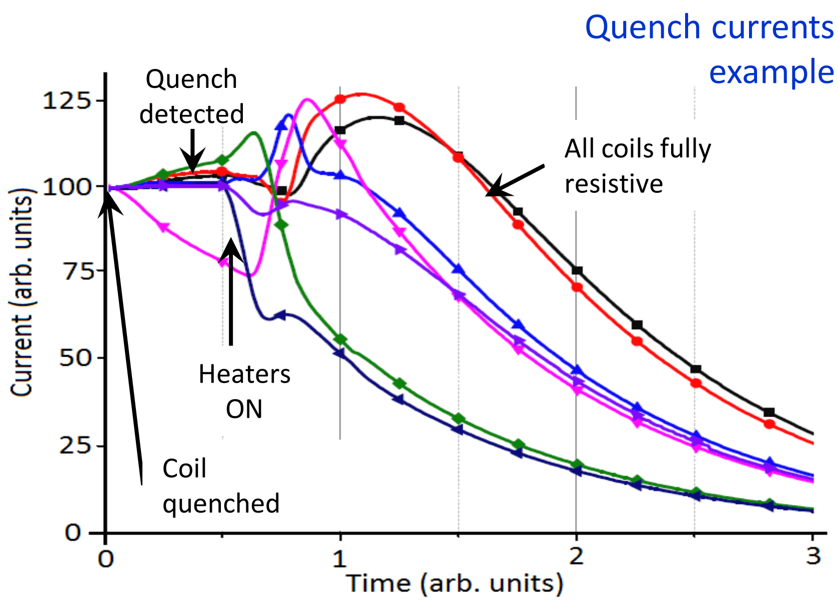
MRI quench protection:

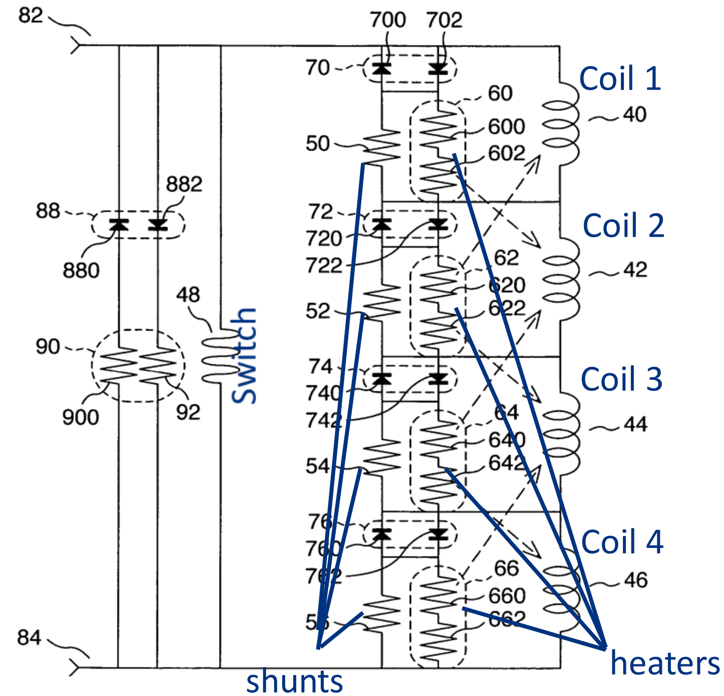
- Passive detection: no external circuit
- Heaters:
  - Resistive: use magnet energy
  - Inductive heating (ancillary)
- Energy released inside cryostat

Quench protection includes:

1. Detection of quench occurs
2. Protection (heater activation)
3. All coils quench
4. Current decays

Quench Protection





- MIIT approach

$$\int_{T_o}^{T_{max}} \frac{C_p(T)}{\rho(T)}\, dT = \int_0^{t_0} J(t)2\, dt$$

- Need fast detection and heater activation and fast normal zone propagation

US Pat. 7,196,883 (M. Tsuchiya et al, Hitachi, 2007)

- Detection controlled by diode threshold voltage
- Extensive and fast heater activation
- Voltage clamping

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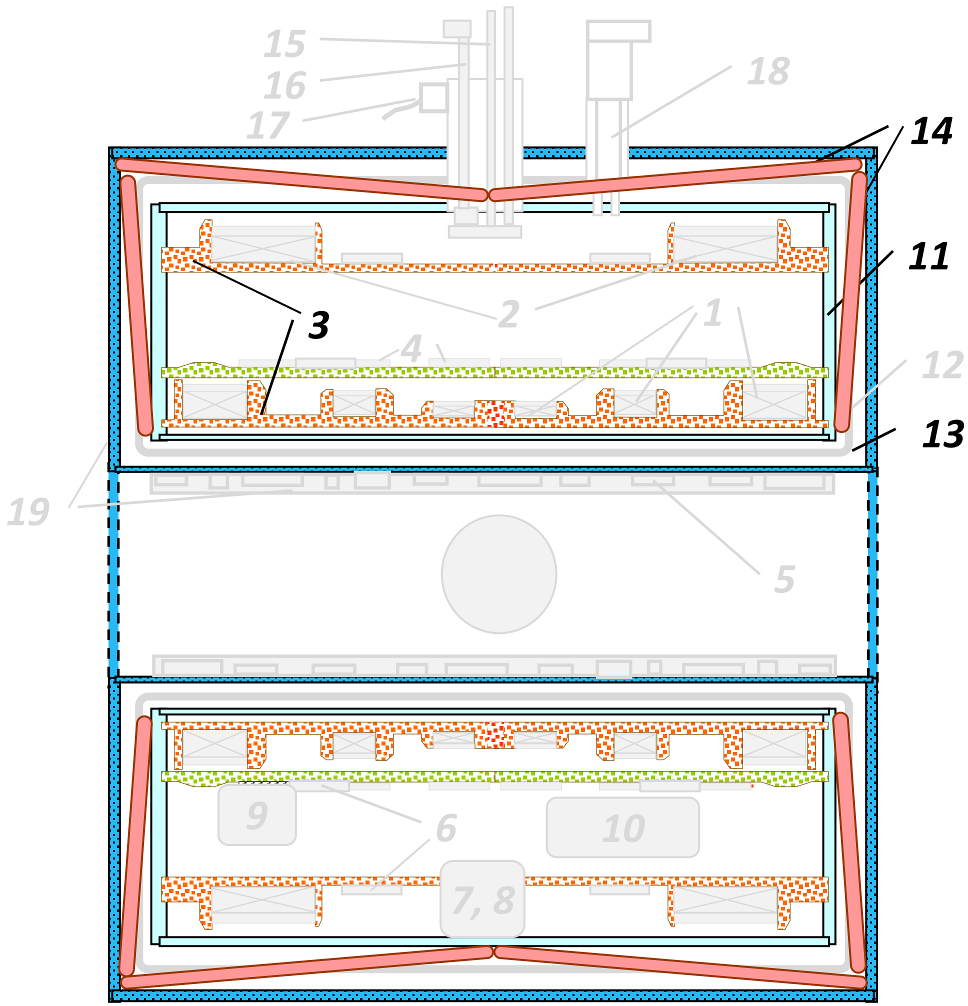
Magnet Support Structure

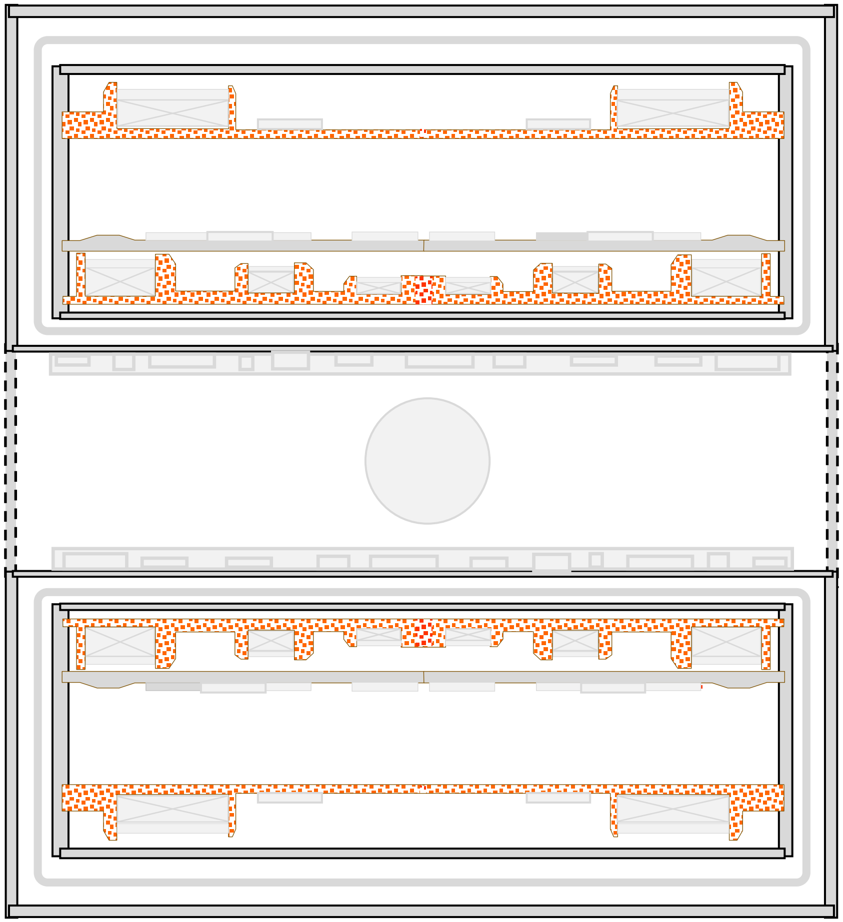


	Element	Function
1	Main coils	Create main homogeneous field
2	Bucking coils	Stray field control
3	Structure (coil form)	Support of inter-coil forces
4	Active shims (CC)	Manuf. tolerance compensation (lower orders)
5	Passive shims	Manuf. tolerance compensation
6	B0 coil	Moving metal compensation
7	Main switch	Persistent circuit (open during ramp)
8	Quench switch	Quench spreading between coils
9	CC switches	Enable current input in CC
10	Quench protection elements	Coils voltage and temperature control during quench
11	Helium vessel	Magnet operational environment
12	Thermal shield	Control of cold-mass thermal load
13	Vacuum vessel	Control of thermal load
14	Suspension	Mech. support of cold-mass & shield
15	Main leads	Current input in magnet
16	Shim lead	Current input in active shims (CC)
17	Instrumentation	Monitor main magnet parameters
18	Cold-head w/ re-condenser	Cryostat heat loads management with zero boil-off
19	Gradient interfaces	Mechanical support and acoustic IF

Coils supported by structures and suspension to vacuum vessel

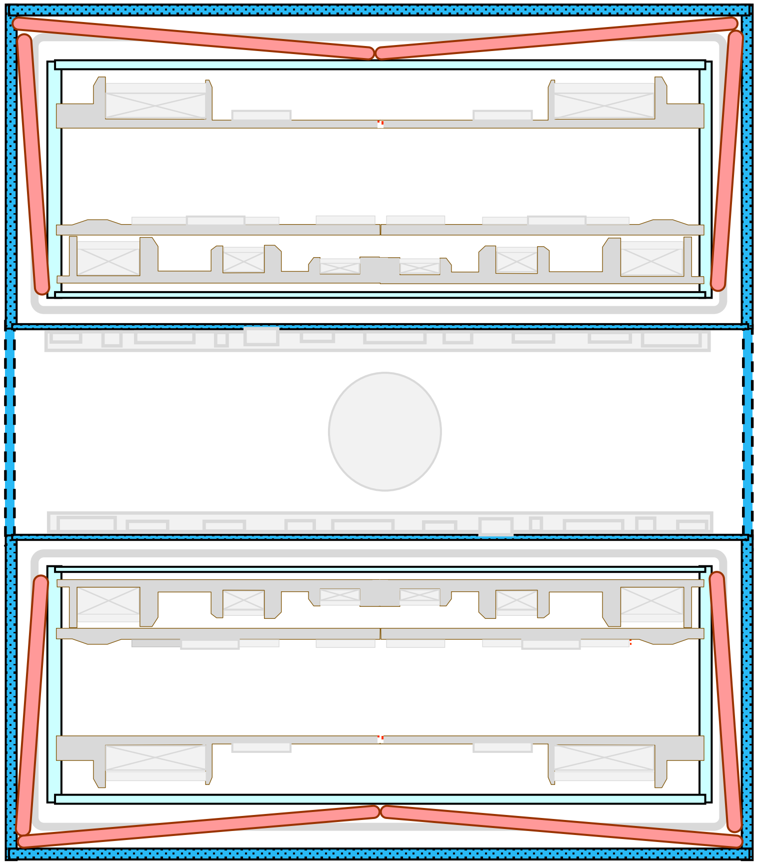
Coil Support Structure

- Function
  - Supports coil during winding
  - Supports coil-coil interaction force
- Design Considerations
  - Strong structure support
  - Light weight
  - Low cost
- Material
  - Aluminum
  - Stainless steel
  - GFRP

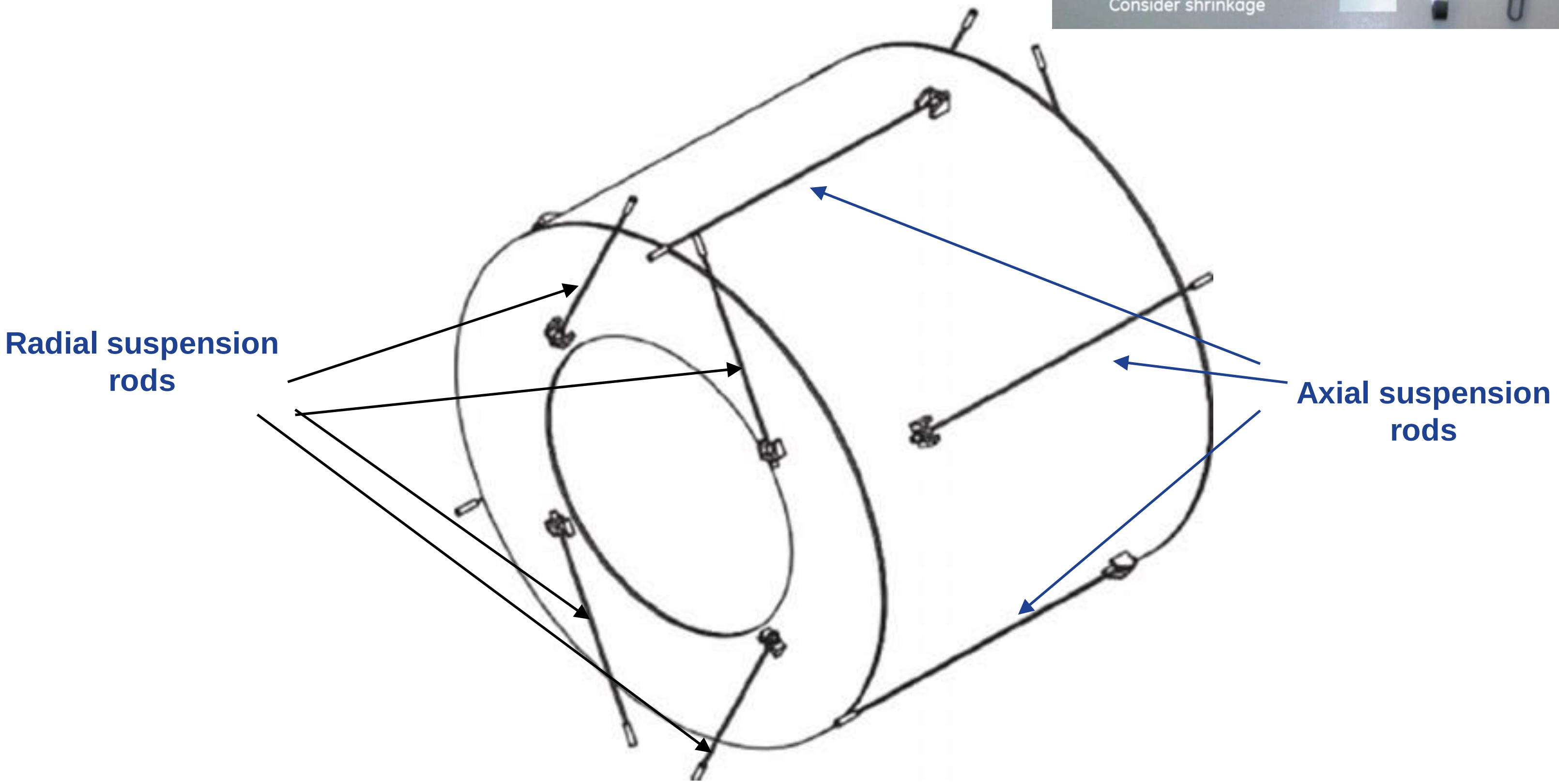


Cold-mass Suspension

- Function
  - Suspend coil mass to vacuum vessel
  - For regular operation + transportation
  - Minimize heat leak to cold-mass
- Design Considerations
  - Strong
  - Low thermal conductivity
  - Small Cross-sectional area
  - Long length
- Material
  - GFRP
  - CFRP
  - Stainless steel
  - Titanium rods



Suspensions



Source: Zhang, et. al., IEEE Trans. Appl. Supercond., V25, #2, 2015

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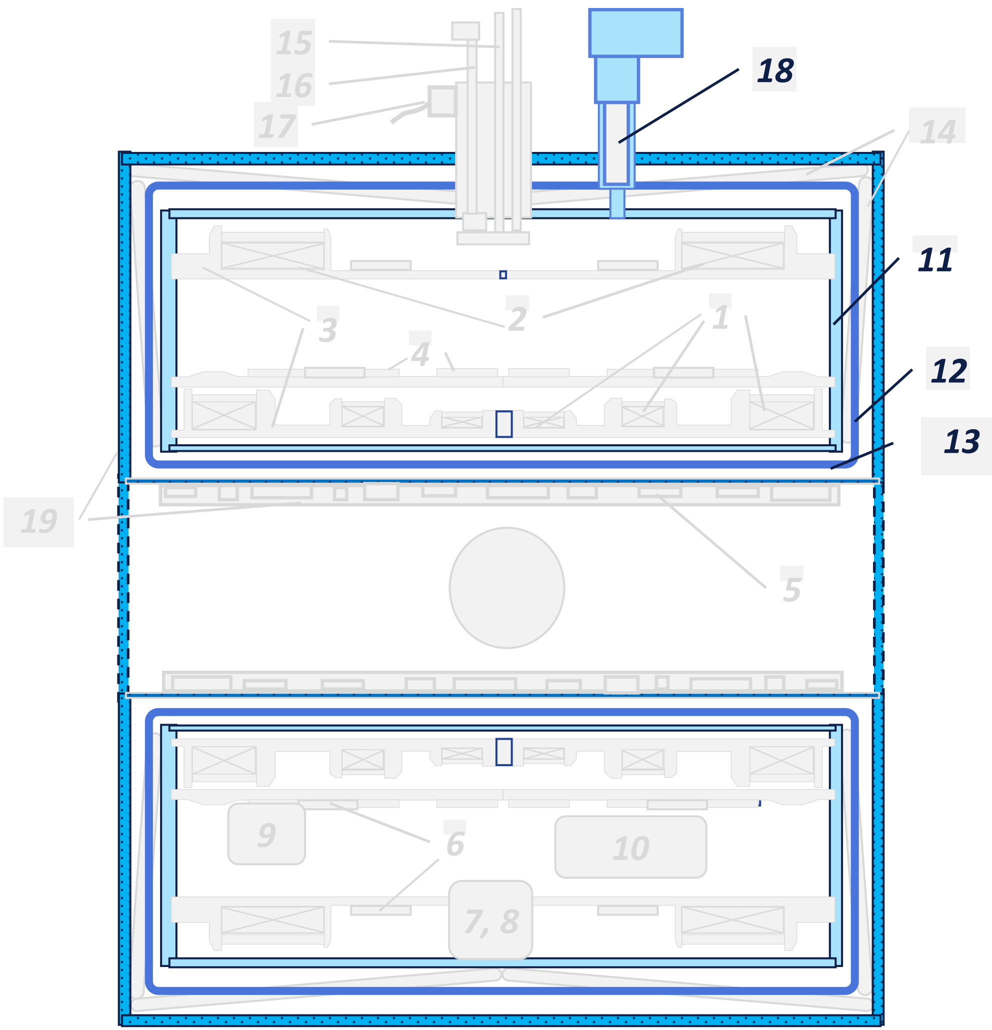
Magnet Cryogenic System



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14	Suspension	Mech. support of coldmass & shield
15	Main leads	Current input in magnet
16	Shim lead	Current input in active shims (CC)
17	Instrumentation	Monitor main magnet parameters
18	Cold-head w/ re-condenser	Cryostat heat loads management with zero helium boil-off
19	Gradient interfaces	Mechanical support and acoustic IF

Helium vessel, thermal shield, vacuum vessel, and cryo-cooler

Magnet Cryostat

Primary Goal

- Reduce heat load to the cold-mass (liquid helium temperature)
- Reduce or eliminate LHe boil off

Three types of heat transfer

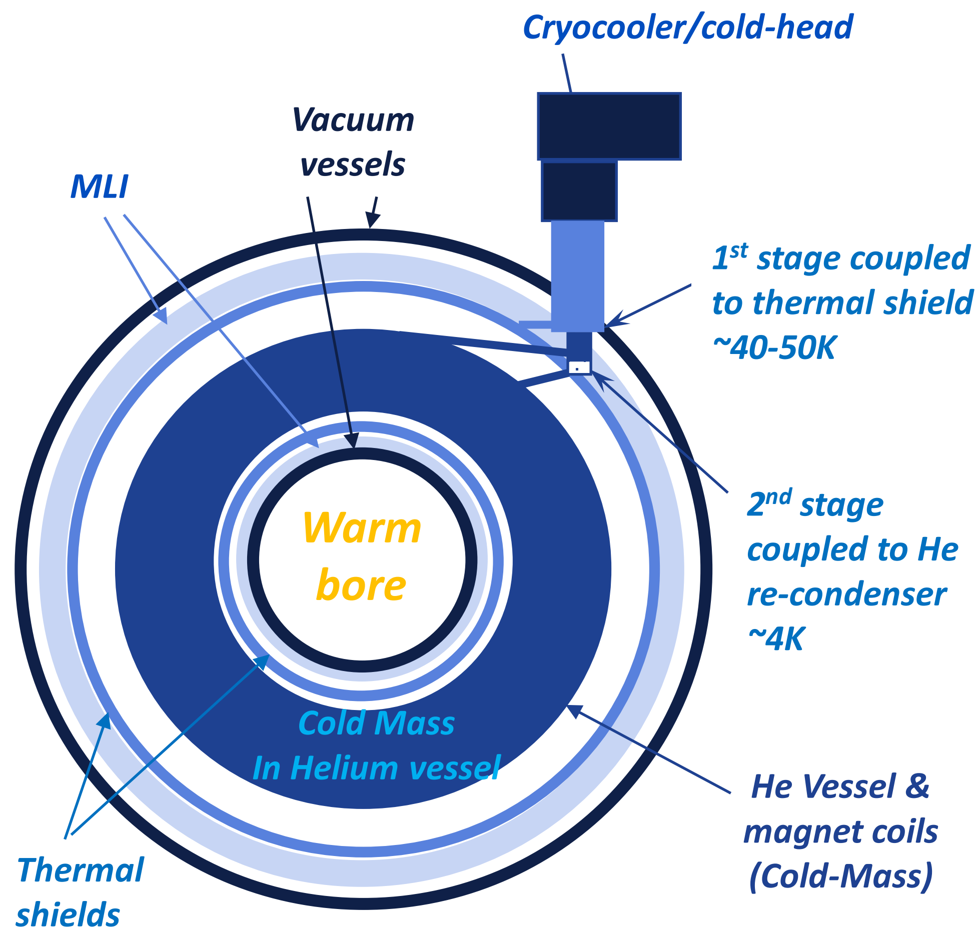
- Convection
- Conduction
- Radiation

Reduce heat load

- Convection → vacuum
- Conduction → suspension w/ composite materials
- Radiation → thermal shield + Multi-layer-insulation (MLI)

Provides cooling

- Cryo-cooler/cold-head



Cryostat keeps superconductors cool

Vacuum Vessel

- Function
  - Holds vacuum
  - Provides structural support
- Design Considerations
  - Strong
  - Low cost
- Material
  - **Stainless steel**
  - **Aluminum**
  - Steel
  - Composites

Thermal Shield

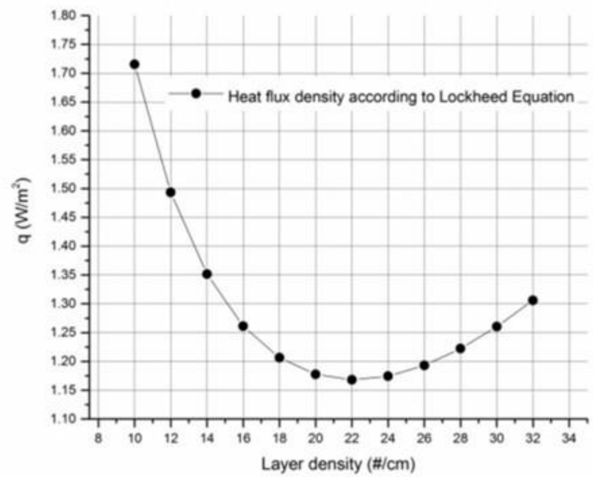
- Function
  - Blocks radiation heat
  - Provides thermal stationing
- Design Considerations
  - Operating temperature 40-60K
  - Connected to 1st stage of cold-head
  - Highly thermal conductive
- Material
  - **Aluminum**, various grades
  - Copper

Multilayer Insulation (MLI)

- Invented by Sir Dewar in 1900
- Developed in space industry in 1950's
- Thin plastic sheets (Mylar or Kapton)
- Metalized on both sides (Al or Ag)
- Separated by thin cloth meshes or scrim
- Loosely packed between vacuum vessel and thermal shield
- Blocks 90-95% of radiation heat

- **Typical number of layers 20 – 40**

Source: PRWeb



Cryo-cooler

Cooling power

1-1.5 W @ 4 K to cold-mass

~ 40W@ 40 K to thermal shield

Design Considerations

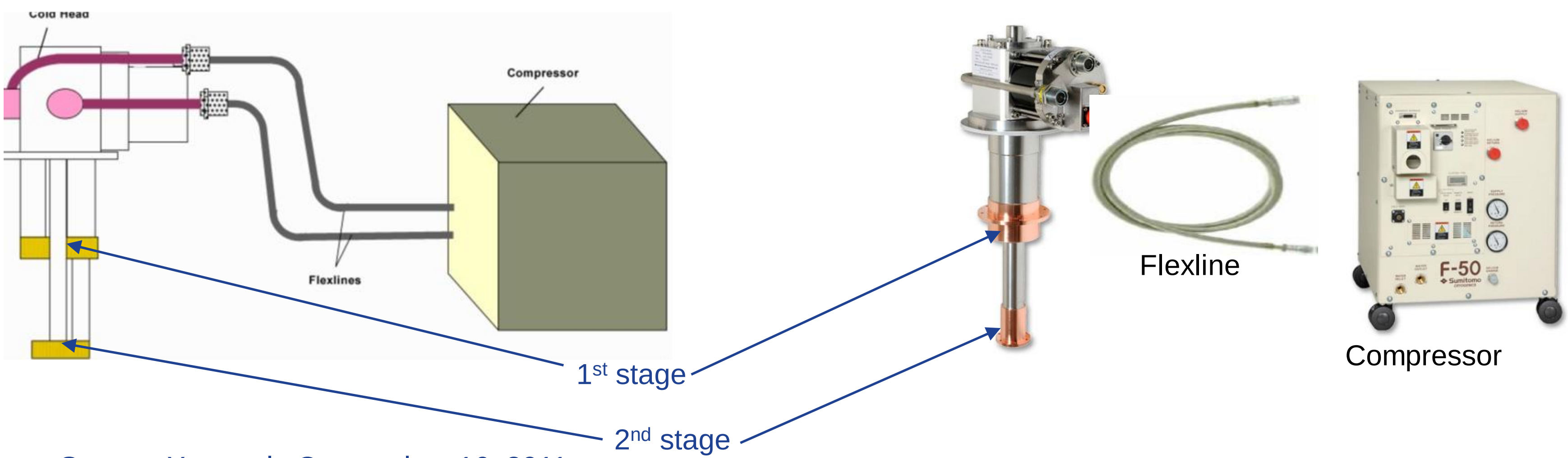
GM or Pulse-type coolers

Cold-head orientation (PT for vertical only)

Maintenance and service

Components of a cryo-cooler system

– Cold-head
– Compressor
– Flex helium lines



Source: Xu et. al., Cryocoolers 16, 2011

Source: Sumitomo (SHI)

Agenda

- Introduction
- Requirements to MRI magnet
- Electromagnetic design
- Structural design
- Cryogenic system
- Conductor
  - LTS
  - MgB_2 and HTS
- Conclusion. Q&A

LTS conductor - NbTi

Why NbTi

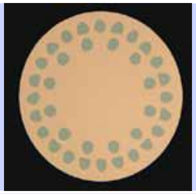
- **Mature**, manufacturing-friendly, optimized for MRI
- Mechanically very **strong**
- Available in **long lengths** with guaranteed properties
- **Lowest-cost** superconducting material
- Con: low critical temperature T_c
  - Expensive refrigeration
  - Low stability: may quench

MRI industry uses

- 3,000 to 5,000 tons/yr (including copper)
- 65%-75% of all NbTi conductor (by weight)
- More than 50% of NbTi alloy

NbTi Conductor for MRI

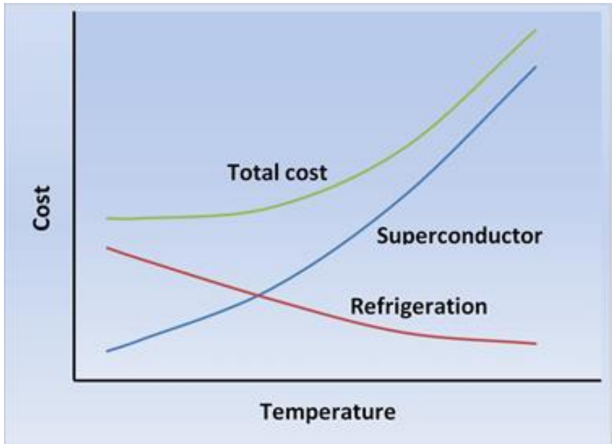
Two conductor types

	Wire-in-channel (WIC)	Monolith
		
Shape	Rectangular	Round or rectangular
Size (typical)	>1 mm height	0.5 mm to 2 mm
Insulation (typical) Break-down voltage	Polyester braid, 150 um thick ~500 V	Formvar, 40 um thick >2,000 V
Cu : NbTi range	5 : 1 to 20 : 1	0.8 : 1 to 8 : 1
Current density in coils	Lower	Higher (1.5 – 2x)
Impact on magnet	• Heavier • Dry-wound and/or VPI • Low thermal conductivity: not fit for cryogen-free magnets	• Lower weight, more compact • Dry-wind or wet wind • Fit for conduction-cooled magnets

Superconductors beyond NbTi

MgB_2, HTS advantages

- Higher-Tc materials may help to reduce installation and life-cycle cost:
  - Liquid-cryogen-free, quench-free system
  - Minimize on-site construction
- MgB_2 offers some potential for use in MRI



Trade-off conductor cost vs refrigeration cost

Challenges of MgB2 and HTS application in MRI

- Design
  - Persistent operation (low N-value, SC joint)
  - Quench protection
  - High price
  - Low engineering current density
  - Short piece lengths
- Manufacturing
  - Winding technology
  - SC Joints
  - Defect detection
  - Conductor breakage
  - Magnet yield

Conclusions

- Commercial MRI magnets have reached maturity
  - Efficient, well-integrated magnet design
  - Still, there are opportunities for improvement and growth
- Superconducting MRI scanners
  - The largest commercial application of superconductivity
  - The highest performance
  - Competitive life-cycle cost
- NbTi is the conductor of choice for commercial MRI magnets

Thank you

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