Superconductors for Application in Detector Magnets

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1. Critical parameters
2. Practical superconductors
3. Temperature margin
4. Stability criteria
5. Application in Magnets
Superconducting Magnets - why so relevant?

Superconductivity = zero DC resistance = no Ohmic loss

No power consumption, except for refrigeration
- lower power bills

Ampere turns are cheap, so do not need iron, except for shielding
- higher magnetic field
- higher energy density or less volume
- reduced capital cost

High current density
- compact windings
- high gradients, high forces
- higher particle/beam density

But

Superconductors suffer losses when the magnetic field changes
⇒ rise in temperature, there is not much margin
⇒ increase in refrigeration load
1. The critical surface of Niobium Titanium

Niobium titanium, NbTi, is the standard work horse for superconducting magnets.

It is a ductile alloy.

The critical surface is the boundary between superconductivity and normal resistivity in 3 dimensional space.

Material is Superconducting below the surface, and has resistance everywhere above it.

An upper critical field $B_{c2}$ and critical temperature $T_c$ are characteristic of the alloy composition.

Critical current density $J_c(B,T)$ depends on processing.
Filamentary composite wires

For reasons explained later, superconducting materials are always used in combination with a good normal conductor such as copper.

To ensure intimate mixing between the two, the superconductor is made in the form of fine filaments embedded in a matrix of copper.

Typical dimensions are:

- wire diameter = 0.3 - 1.3 mm
- filament diameter = 5 – 50 μm.

For electromagnetic reasons, the composite wires are twisted so that the filaments look like a rope.
Critical Temperature \( T_c \)

\[
3.5 \, k_B \, T_c = 2 \, \Delta(0)
\]

\( k_B \) is Boltzmann's constant
\( \Delta(0) \) is the energy gap (binding energy of Cooper pairs) of at \( T=0 \).

Critical Field \( B_c \):
Type I superconductors show the Meissner effect. Field is expelled when sample becomes superconducting.

It costs energy to keep the field out. Critical field happens when the condensation energy of the superconducting state is just equal to the energy penalty of keeping the field out.

\[
\frac{B_c^2}{2\mu_0} = G_n - G_s
\]

where \( G \) is the Gibbs Free Energy of the normal/superconducting state. BCS theory says

\[
G_n(0) - G_s(0) = \frac{1}{2} N_F (\Delta(0))^2
\]

where \( N_F \) is the density of states at the Fermi surface of metal in normal state - calculate it from:

\[
\gamma = \frac{2}{3} \pi^2 \, N_F \, k_B^2
\]

where \( \gamma \) is Sommerfeld coefficient of electronic specific heat

\[
C = \gamma \, T + A \, T^3
\]
Critical temperature and critical magnetic field

Combining the previous equations:

\[ B_c(0) = \left( \frac{3\mu_0}{2} \right)^{\frac{1}{2}} \frac{3.5}{2\pi} \gamma^2 T_c = 7.65 \times 10^{-4} \gamma^2 T_c \]

Thermodynamic critical field \( B_c \)

so like the critical temperature, \( B_c \)
is defined by the chemistry
typically for NbTi \( \gamma \sim 10^3 \) J m\(^{-3}\) K\(^{-1}\)
so if \( T = 10 \) K \( B_c = 0.24T \)

Thus: Type I superconductors are useless for magnets!

Note: Meissner effect is not total, the magnetic field actually penetrates a small distance \( \lambda \) the London penetration depth.

Another characteristic distance is the coherence length \( \zeta \); the minimum distance over which the electronic state can change from superconducting to normal.
Critical properties of type II superconductors

Theory of Ginsburg, Landau, Abrikosov & Gorkov (GLAG)

defines the ratio \( \kappa = \lambda / \xi \)

If \( \kappa > 1/\sqrt{2} \) the magnetic field can penetrate in the form of discrete fluxoids - Type II

\[ \phi = h / 2e \]

a single fluxoid encloses flux

\[ \phi_o = \frac{h}{2e} = 2 \times 10^{-15} \text{Webers} \]

where \( h = \) Planck's constant, \( e = \) electronic charge

upper critical field

\[ B_{c2} = \sqrt{2} \kappa B_c \]

in the 'dirty limit'

\[ \kappa \approx 2.4 \times 10^6 \gamma^2 \rho_n \]

where \( \rho_n \) is the normal state resistivity

! best superconductors are best resistors!

thus the upper critical field:

\[ B_{c2} = 3.1 \times 10^3 \gamma \rho_n T_c \]

for NbTi: \( \gamma \approx 900 \text{ J m}^{-3} \text{ K}^{-2} \), \( \rho_n \approx 65 \times 10^{-8} \Omega \text{ m} \), \( T_c = 9. \text{ K} \), hence

\[ B_{c2} = 18.5 \text{ T} \]
Critical current density

Flux lines consist of resistive cores with super-currents circulating round them.

\[
d = \left( \frac{2 \phi_0}{\sqrt{3} B} \right)^{\frac{1}{2}} = 22 \text{nm at } 5T
\]

a uniform distribution of flux lines gives no net current, so \( J_c = 0 \), but a gradient produces a net current density

\[
\nabla \times B = \mu_0 J = J_c
\]

• gradients must be produced by inhomogeneities in the material, like dislocations or precipitates
• process is known as flux pinning
• flux pinning is an irreversible lossy process

precipitates of \( \alpha \) Ti in NbTi

Flux lines lattice at 5 T on the same scale.
Critical properties summary

- **Critical temperature**: choose the right material to have a large energy gap or 'depairing energy'.
- **Critical magnetic field**: choose a Type II superconductor with a high critical temperature and a high normal state resistivity.
- **Critical current density**: mess up the microstructure by cold working and precipitation heat treatments, the way in which we have any control.

Similar effects in high temperature superconducting materials: flux line lattice in BSCCO.
Of all metallic superconductors, only NbTi is ductile.

Others are brittle intermetallic compounds.

Of all superconductors, only a few are successful!

Meaning: you can make wires for acceptable cost.
In designing a magnet, what really matters is the overall engineering current density $J_{\text{eng}}$

$$J_{\text{eng}} = \frac{\text{current}}{\text{unit cell area}} = J_{\text{supercon}} \times \lambda_{\text{sc}} \times \lambda_{\text{wire}}$$

fill factor in the wire:

$$\lambda_{\text{sc}} = \frac{1}{1 + \lambda}$$

where $\lambda = \text{area ratio of matrix to superconductor}$

typically:

for NbTi $\lambda = 1.5$ to $3.0 \rightarrow \lambda_{\text{sc}} = 0.4$ to $0.25$

for Nb$_3$Sn $\lambda \sim 3.0 \rightarrow \lambda_{\text{sc}} \sim 0.25$

for B2212 $\lambda = 3.0$ to $4.0 \rightarrow \lambda_{\text{sc}} = 0.25$ to $0.2$

$\lambda_{\text{wire}}$ takes account of space occupied by insulation, cooling channels, mechanical reinforcement etc and is typically $0.7$ to $0.8$

So typically $J_{\text{eng}}$ is only $15\%$ to $30\%$ of $J_{\text{supercon}}$
Screening currents and the critical state model

When a superconductor is subjected to a changing magnetic field, screening currents are induced.

**Screening currents** are in addition to the **transport current**, which comes from the power supply.

They are like eddy currents but, there is no resistance, they don't decay.

Usual model is a superconducting slab in a changing magnetic field $B_y$

- assume it is infinitely long in the $z$ and $y$ directions - simplifies to a 1d-problem

- $dB/dt$ induces an electric field $E$ which causes screening currents to flow at critical current density $J_c$

**Critical state model** or **Bean model**:

- in a 1d infinite slab geometry, Maxwell's equation says
  \[
  \frac{\partial B_y}{\partial x} = -\mu_0 J_z = \mu_0 J_c
  \]

A uniform $J_c$ means a constant field gradient inside the superconductor.

Everywhere in the superconductor the current density is either $J_c$ or zero.
The flux penetration process

plot field profile across the slab

field increasing from zero

field decreasing through zero

fully penetrated
Conclusion for basic properties

• Superconducting magnets do not use power (dc), but need to be cooled.
• They produce high magnetic fields - but in changing fields they suffer ac loss.
• Two types of superconductor
  - type I: not suitable for high field
  - type II: good for high field - but must work hard to get current density.
• All magnets use type II, usually NbTi (even 50 years after its discovery).
• Performance of superconductors is described by the critical surface in the $B \cdot T \cdot J$ space
  - properties in $B$ and $T$ space are reversible, determined by the chemistry,
  - properties in $J$ space are irreversible and lossy, determined by flux pinning inhomogeneities.
• Engineering current density is what counts for magnet performance.
• A changing magnet field induces persistent currents in superconductors.
• Persistent currents can be described by the Critical State model,
  - they are a major cause of ac loss.
2.1 Practical Conductors, NbTi

Cubic alloy, isotropic

History of superconductors inventions

Tc : 11 K
Bc2 : 13 T

Very well developed
~1 € / kA m
Manufacturing NbTi wires

- Vacuum melting of NbTi billets
- Hot extrusion of the copper NbTi composite
- Sequence of cold drawing and intermediate heat treatments to precipitate α-Ti phases as flux pinning centres
- For very fine filaments, must avoid the formation of brittle CuTi intermetallic compounds during heat treatment - usually done by enclosing the NbTi in a thin Nb shell
- Twisting to avoid coupling
2.2 Nb₃Sn wires, 3 routes to make it

- **Bronze Process**
  - α-Bronze
  - Nb Filaments

- **Powder-in-tube Process**
  - NbSn₂ + Cu Powder
  - Nb

- **Internal Sn Process**
  - Cu
  - Nb filaments
  - Sn

**Bronze Route, Bruker EAS**

- **Internal Tin, Oxford OST**

**NbSn₂ Powder in Tube, Bruker EAS**

**Tc**: 18 K

**Bc2**: 30 T

Cubic inter-metallic, isotropic

~ 1000 A/mm² (bronze)
~ 3000 A/mm² (IT/PIT) at 12T and 4.2 K

Well developed, still improving

~ 5-25 €/kA m

All Nb₃Sn by thermal diffusion of Sn to Nb after coil winding.
2.3 BSCCO and YBCO

Generation I: Bi-Sr-Ca-Cu-O

B2223: $T_c \sim 108$ K, tape, no wire! R&D support halted except in Japan.

B2212: $T_c \sim 92$ K and can be made as wire! Modest investments to further develop, mainly by Oxford-OST.

Generation II: Coated YBCO conductor

Y-Ba-Cu-O (Y-123)

$T_c \sim 92$ K, basis for new generation technology (IBAD, RABiTS or ISD) available already in up to 1 km length.

~ 100-300 €/kA m!
YBCO is the dream conductor for 5-20 T magnets operating at 50-60 K!
Superconductors for magnets

- **Y123** in a magnet, not in \( // \) field!
- **B2211** may do better than Y123 when anisotropy is considered
- **MgB\(_2\)** not for high field magnets but niche market 1-5T, 4-20K
- **NbTi** for high field up to 9 T and 4 K and 11T, 1.8 K
- **Nb\(_3\)Sn** for any magnets of 9-20T
- **B2212 or Y123** for DC magnets of 17-40T provided cost comes down drastically

Minimum practical current density
3. Critical temperature, field dependency

Superconducting Phase ($J_c$ vs. $B$ and $T$).

So far constant temperature has been assumed i.e. no heat release in Critical State Model.

For maintaining the superconducting state, the conductor must operate below the critical surface determined by critical current, magnetic field and temperature.

For NbTi the critical area is bounded by:

- $T_c = 9.2$ K; $B_{c2}(0) = 14.5$ T
- $B_{c2}(T) = B_{c2}(0) \left[1 - \left(T/9.2\right)^{1.7}\right]$  
- $T_c(B) = Tc(0) \left(1 - \left(B/14.5\right)\right)^{0.59}$
- $B_{c2}(4.2K) = 10.7$ T
- $T_c(5T) = 7.16$ K

Similar relations are found for Nb$_3$Sn and BSCCO 2212 and 2223.
Temperature margin

When a transport current flows, the onset of resistance is further reduced from $T_c$ to $T_{cs}$, the current sharing temperature

$$T_{cs}(B,I) = T_b + (T_c(B) - T_b) \left(1 - \frac{I}{I_c}\right) \quad T_{cs}(5 \ T, I_c/2 \ A) = 5.7 \ K \ only!$$

- So we lost a lot of margin from 9.2 K $\rightarrow$ 7.2 K $\rightarrow$ 5.7 K versus 4.4 K.

- At 4.4 K, at 50% $I_c$ and 5 T there is only 1.2 K margin !

- At 75% of $I_c$ we get 0.7 K, so we never can operate very near to $I_c$ !

- Following $\Delta T = Q / c(T)$
  release of energy (heat) from various sources will cause a temperature rise and thus the superconducting state is very seriously in danger.

- The heat that can be absorbed without reaching $T_{cs}$ is the enthalpy difference $\Delta H = \int c(T) \ dT$ between $T_{cs}$ and $T_o$. 
We can distinguish various sources of heat

**Heat pulses, transients**
- Flux jumps
- Cracking of resin
- Wire motion; load in $\mu$J/mm$^3$

**Continuous heating**
- Flux flow
- Losses in pulsed magnets and at fast ramp down
- AC losses at 50Hz, energy applications, due to alternating current and fields
- Current sharing due to bad sections in the conductor
- Joints between superconductors, usually $< n \Omega$, no problem
- Synchrotron radiation in accelerators
- Neutron radiation in tokamaks.
Release of heat and extremely low heat capacity

Why is release of heat so critical at 4 K?

- Heat capacity is strongly T-dependent and extremely low below 10 K for all materials.
- Copper-NbTi composite:
  \[ C_p(T) = \eta((6.8/\eta + 43.8)T^3 + (97.4 + 69.8 B)T) \mu J/mm^3K, \]
  which is at 5 T and 40% NbTi in Cu matrix:
  - 2.5 \mu J/mm^3K at 4.2 K and
  - 0.5 \mu J/mm^3K at 1.9 K!
  - 2.5 \mu J/mm corresponds to a movement in a 1 mm wire at 5 T and 500 A of 1 \mu m only!

Heat release of \mu J/mm^3 has to be avoided, otherwise magnet will quench
- avoid friction and slip-stick by introducing low friction sliding (kapton films wrapped around wires and cables)
- avoid any displacement, vacuum impregnation of coils
- avoid resin cracks, avoid local stress concentrations at bonded surfaces
Minimum Propagation Zone

Examples of MPZ in various wires:
- In a bare NbTi wire or filament:
  take $5 \text{T}; 3000 \text{A/mm}^2; \rho = 6 \times 10^{-7} \text{Ωm}; \lambda = 0.1 \text{W/mK}; T_c = 7 \text{K}$
  and we find 0.3 μm only
  in a 0.3 mm wire this requires about 1 nJ to reach $T_c$!
- NbTi with CuNi matrix would give 3 μm and 0.1 μJ!
- Such wire is extremely sensitive to any heat pulse

**Remedy:** reduce $\rho$ by using copper matrix ($3 \times 10^{-10} \text{Ωm}$, factor 2000) and increase $\lambda$ by using copper (> 200 W/mK, factor 2000 again!)

Thus, we see how wonderful copper is, without copper no sc magnets!

 ✓ factor 2000 improvement, from μm to few mm and μJ range

 ✓ for a typical LHC cable we get about 15 mm

 ✓ and in the ATLAS conductor (600 mm$^2$ pure Al and 20 kA) we get about 500 mm!
Achieve stable performance: Adiabatic Filament Stability

Field penetration in filaments

- Field penetrates according the Critical State Model
- In the filament magnetic energy is stored
- When disturbed, the heat must be taken up by the enthalpy of the filament
- A disturbance $\Delta T_1$ will cause a $-\Delta J_c$, so flux motion, leading to $E$, this leading to heat and so again a $\Delta T_2$
- When $\Delta T_2 > \Delta T_1$, the process will accelerate and the flux profile collapses
- Based on simple slab model, the adiabatic stability criterion is found:

$$d_{fil} \cdot J_c < (3 \cdot c \cdot (T_c - T_o) / \mu_o)^{1/2}$$

Thus we see a maximum in the filament thickness for a given current density, to guarantee stability.
Adiabatic Filament Stability

Example for NbTi

- Specific heat $c = 5600 \text{ J/m}^3$; $T_c(5T) = 7.2 \text{ K}$, $T_o = 4.2 \text{ K}$ and $J_c = 3000 \text{ A/mm}^2$, we find $\sim 70 \mu \text{m}$.
- Filament diameter must be adapted to the $J_c(B)$.
- Must be much smaller than $70 \mu \text{m}$ below 5T (AC applications, transformers).

Consequences:

- Split the NbTi section required for the $I_c$ into many small filaments.
- We see a fundamental requirement for small filaments besides cooling and application related arguments like reduction of magnetization loss.
- Disadvantages: filaments are now coupled by transverse fields, extra AC coupling loss requires filament twisting, cost.
Adiabatic Wire Self field Stability

Filaments coupled by self field

- Adiabatic filament stability requires fine filaments in a matrix. These can be de-coupled for transverse fields by twisting.
- But are still fully coupled by the self-field.
- Again following the CSM, we see the field penetration profile disturbed by a $\Delta T$.
- Field profile has to change, penetrates deeper, causing heat dissipation taken up by the enthalpy up to a certain limit.
- Assuming $\eta = \text{sc/total ratio}$ and current density $\eta J$.
- We find for the adiabatic self-field criterion:

$$D \cdot \eta J < (4c (T_c - T_o)/\mu_o)^{1/2} f (I/Ic)$$

where $f (I/Ic) = 1/(-0.5 \ln(I) - 3/8 + i^2/6 - i^4/8)$

Thus we see a maximum wire diameter for a given $Jc$ and $I/Ic$. 
Self-field Stability: cable examples

ITER cable for central solenoid
- 65 kA at 13.5 T, ~1152 Nb3Sn wires parallel in a twisted multi-stage cable.
- Cable layout with 5 stages: 1x3x4x4x4x6.
- Wire 0.81 mm, filaments 4 μm.
- the strands take all positions in the cable to guarantee equal inductance and current sharing.

LHC type Nb3Sn Rutherford cable
- 33 stands single stage twisted.
- 13 kA at 11 T.

ATLAS cable
- Al stabilized 40 strands Rutherford cable.
- 65 kA at 5 T.
Conclusion

Due to the very low heat capacity of materials at low temperature heat production of $\mu$J/mm$^3$ (kJ/m$^3$) will cause quenches in wires and magnets.

Premature quenching, training or even worse, permanent degradation are the dominant factors determining the success of a magnet application.

A mature coil design verified with model magnets regarding wire displacements in combination with impregnation and low friction techniques is crucial.

Various stability criteria were developed and have to be respected.

The criteria largely define the shape and internal layout of wires (many thin filaments in Cu) and cables (many parallel wires, fully transposed) and the way cooling is applied (edge, bath or internal forced flow cooling).

The next issue is when despite all this a quench occurs, how the magnet can be switched off safely and resume operation.
Why magnets require High Current and Cables

Magnetic field and stored energy

\[ B \propto N \cdot I \quad E \propto B^2 \cdot \text{Volume} \]

Inductance \[ L \propto N^2 \]

- Need safe survival from a quench
- Energy dump within short time before conductor burns out

\[ \Rightarrow \text{Thus low } N, \text{ high current } I \]

Also \[ I_{\text{safe}} \propto J \cdot E / V_d \], kV-range for \( V_d \), with usual current densities this leads to \( 10-100 \) kA

- Given strand currents of typically 100 to 500A, we need for large scale magnets multi strand cables of 20-10000 strands,

No escape!
Scaling: $I_{\text{safe}} \propto J \times B^2 \times \text{Volume}$

- 0.0001 m$^3$ HF insert model, $\sim 200$ A
- 2 m$^3$ MRI magnet, 200-800 A @ 1-3 T, $\sim$10 MJ
- 25 m$^3$ ATLAS solenoid, 8 kA @ 2T, 40 MJ
- 50m$^3$ LHC dipole, 12 kA @ 8.3 T
- 400 m$^3$ HEF detector magnet, 20 kA @ 4 T, 2.6 GJ
- 1000 m$^3$ ITER magnets, 40-70 kA @ 10-13T, 50 GJ
High current conductors are requested

200 A HTS tape

no

65000 A@5T Al-NbTi/Cu

yes

One cannot build large scale magnets from single NbTi-Nb$_3$Sn-B2212-Y123 wires or tapes

We need superconductors that can be cabled and survive a quench!
Market of laboratory magnets in many variants up to 20 T at 1.9 K
NMR spectroscopy magnets up to ~ 22 T, 950 MHz
Pushing up to 30 T using HTS
New high field magnets as user facilities

Beyond 20 T systems become too expensive for single labs and we move to user facilities

A new and unique fully superconducting 32 T magnet user facility, YBCO insert pancake coils

A nested HTS coil in an existing twin outsert of NbTi/Nb3Sn

- 172 A, 619 H, 9 MJ
- Under Construction at the NHMFL, test in 2013

✓ When successful, a real breakthrough

Courtesy of NHMFL-Tallahassee
Medical NMR, MRI for diagnostics ~ 40000 units installed
It works well due to High Quality NbTi and Persistent Mode
Today standard are 1.5 T but mostly 3 T, actively shielded
- Functional MRI for brain research and treatment
- Real time MRI, filming
- Interventional MRI, surgery
Quest for higher resolutions, higher magnetic field, 7 and 9 T
High-field MRI beyond 3T, 2 examples

9.4 T MRI magnet
90 cm bore and 54 tons
for brain research in combination with PET scanner, to study degeneration processes like Alzheimer and Parkinson decease

11.75 T MRI magnet
at the limit of NbTi at 1.8 K
90 cm bore,
1.48 kA, 338 MJ
5.2 x 5 foot print, 132 tons
Study of central nervous systems “from mice to humans”
Stretching MRI to the limits....
3: Proton Therapy

Medical accelerators providing a p beam for tumor treatment
- 28 p-therapy centers in the world
- 8 operational/planned in Europe

2 Options:
- Large scale facility (like Comet)
- Single compact station (future)

Quest for high-field compact and cost efficient integrated units

Needs some time but could become the 2nd large scale medical magnet application of superconductivity
14 TeV pp collider, a complex with more than 9000 superconducting magnets by far the largest superconducting system in operation
Superconductivity and HE Physics

The Large Hadron Collider could not be realized without exclusive use of superconductivity and high quality magnets.

No Higgs without Superconductivity........
LHC : 7000 km of 12 kA NbTi/Cu cable

LHC type I cables
NbTi/Cu 28 strands
15.1 mm wide
$I_c$ (1.9K, 9T) ~ 20 kA
filament size ~ 5 μm
5: HEF Detector magnets, ATLAS

A Barrel Toroid, two End Cap Toroids and a Central Solenoid provide 2 T for the inner detector ~1 T for the muon detectors in blue

20 m diam. x 25 m length
1000 m$^3$ with field

170 t, 90 km superconductor
700 t cold mass
1320 t magnets

20.4 kA at 4.1 T
1.5 GJ stored energy
4.7 K conduction cooled

10 yrs of construction 97-07

The largest trio of toroids ever built
ATLAS in Amsterdam

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Length</td>
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<tr>
<td>Electronic channels</td>
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The First (1912) and The Largest (2007) 
0.05 m and 25 m
6: Base load e-power with fusion

Advantages
- Large scale and limitless fuel
- Available all over the world
- No greenhouse gases and safe
- No long-lived radioactive waste

Since 1979, worldwide
- 7 sc tokamaks (213 in total),
- 3-8 T on plasma

Recent superconducting machines:
- KSTAR-Korea, EAST-China, SST1-India

2 under construction:
- JT60SA and ITER

and
- 1 Wendelstein type W7X
**ITER magnet system**

Major plasma radius 6.2 m
840 m$^3$ plasma and 15 mA current
Fusion power: 500 MW

First results medio 2025

**ITER**: NbTi and Nb$_3$Sn, no options

DEMO design start soon, still NbTi & Nb$_3$Sn

May be Bi-2212 or YBCO in production plants when multi-kA cables become available and cost has come down drastically........

<table>
<thead>
<tr>
<th>System</th>
<th>Energy GJ</th>
<th>Peak Field</th>
<th>Total MAT</th>
<th>Cond length km</th>
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<td>85</td>
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</table>
7 : Motors and Generators with HTS windings

Example AMSC-USA

36.5 MW ship motor

Conventional  280 t

Superconducting  75 t
**SC generators for wind turbines**

Direct drives saves weight and volume  $\sim \frac{1}{2}$

✓ Makes towers less heavy, cheaper

8 MW unit under development (AMSC)

Interest from European companies growing
8 : Fault Current Limiter using Bi-2212 bulk

Resistive type
Switching bulk
Bi-2212 bifilar coils to resistive state

Main data:
- outer diameter: 58 mm
- superconductor - length: 5.4 m
- superconductor - tube: 300 mm
- superconductor - cross section: 0.24 cm²
- crit. current (65K): 850 A
- protected power (65K): >130 kVA
9: SC Cable 6 km Amsterdam cable under study

- Challenge in length never done before
- Requires adapted cooling system and perfect vacuum system
- Would be nice to see this happening, a real breakthrough
10 : Superconducting JR-MAGLEV in Japan

- JR-Maglev since 1969 pushed forward, records at 580 km/h, nominal 500 km/h
- Summer 2011 : Now first passengers track will be built, very important!
- From Tokyo via Nagoya (in 2027) to Osaka (in 2045) in 1h (now 2h25)
Market of Superconductors

<table>
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<tr>
<th>Year</th>
<th>2007</th>
<th>2009</th>
<th>2011</th>
<th>2013</th>
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<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
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- ~ 5 B€/yr business, growing
- today dominated by MRI and Research Magnets, including NMR and accelerator magnets, >90%
- and workhorse superconductors NbTi and Nb$_3$Sn >90%
From materials to magnets

How to make performing multi-kA conductors that guarantee the magnet not to quench or degrade?

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We need to understand and control the entire chain

- An under developed area of research, but essential to avoid surprises and degraded magnet performance
- Striking examples exist of missing understanding putting large projects at risk
**Conclusion**

Kamerlingh-Onnes’ invention has given us unique new facilities in *Science*: High Field labs, NMR, High Energy Physics, Fusion in *Medicine*: MRI imaging and medical accelerators in *Transport*: Maglev and more...

Superconductors are very successfully applied where no alternatives are present (magnets > 2 T and in a large volume > 1 L).

After 25 years of development, High Temperature Superconductors are also available in km lengths, still a long way to go, to make them cheaper, but their properties are shiny and irresistible.....

A very exciting world of science and technology............