Superconductors for Application in Detector Magnets

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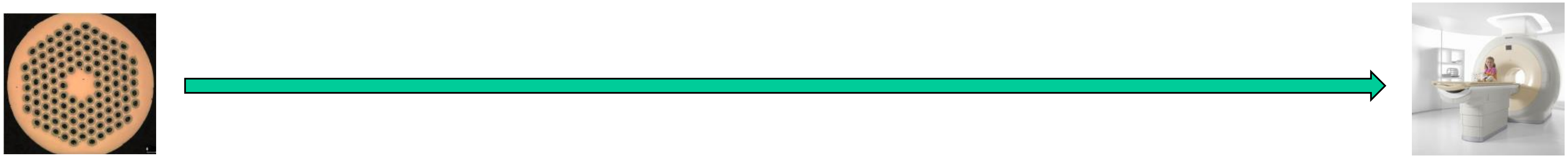
1. Critical parameters
2. Practical superconductors
3. Temperature margin
4. Stability criteria
5. Application in Magnets



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

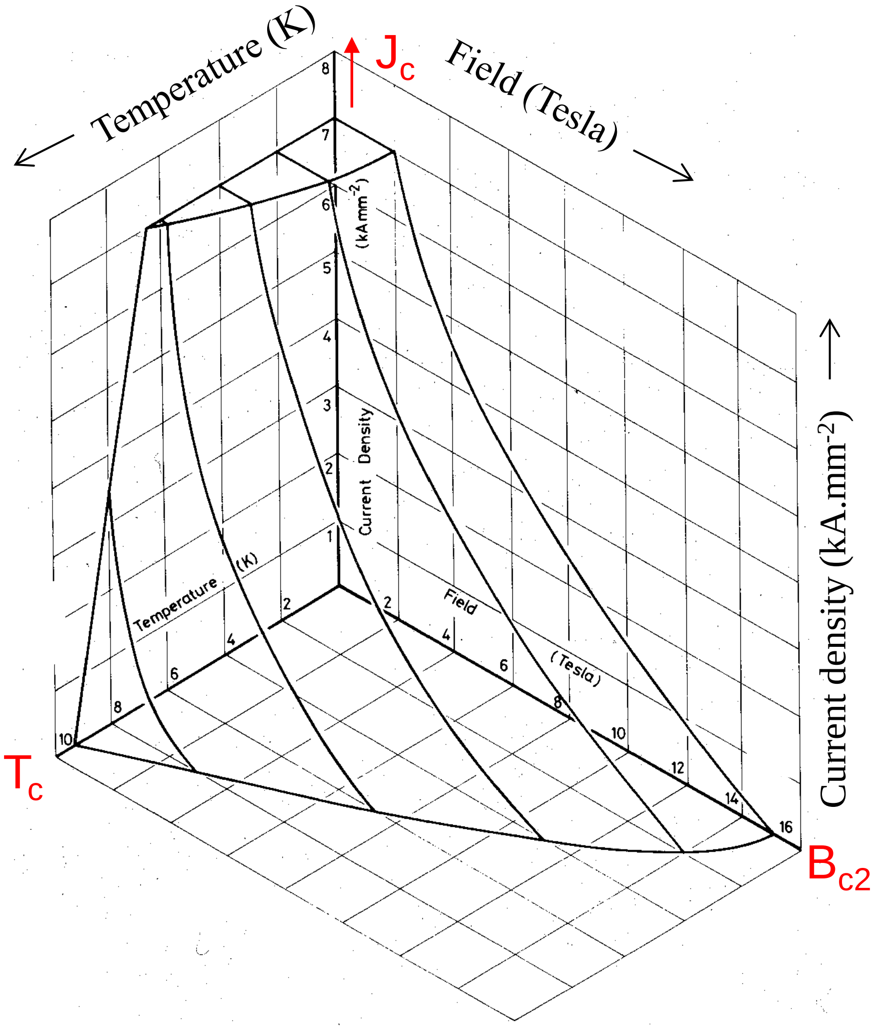
But

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

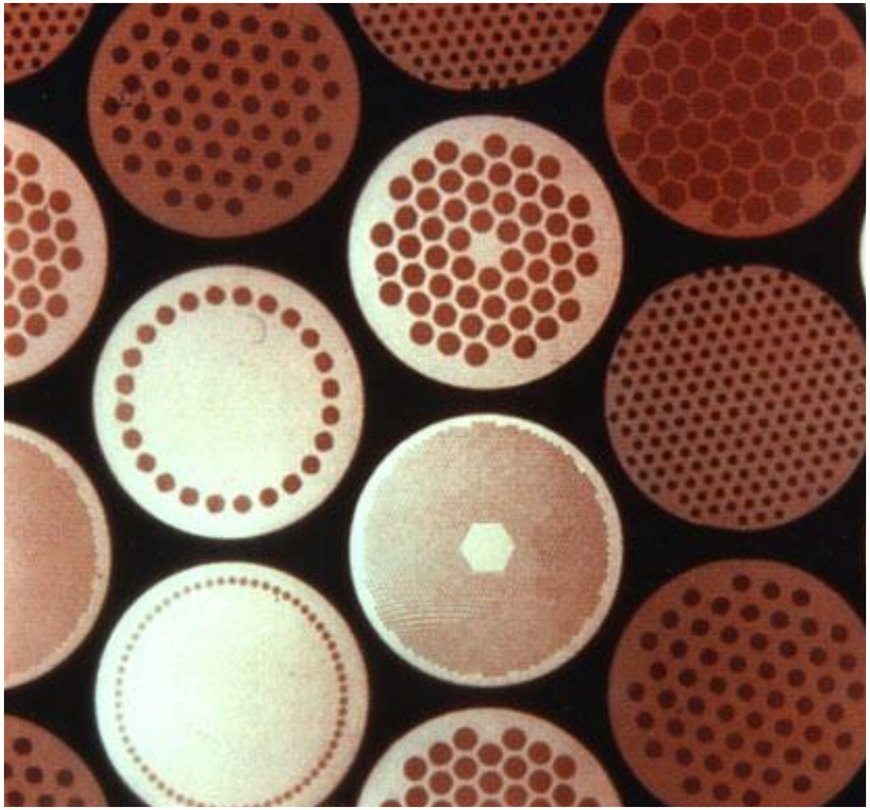
For reasons explained later, superconducting materials are always used in combination with a good normal conductor such as copper.

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

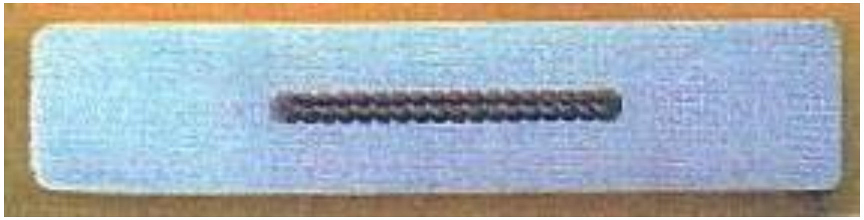
Typical dimensions are:

- 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.



Cross sections of superconducting wires



40 wires in a cable, surrounded by pure aluminium

Critical temperature and critical magnetic field

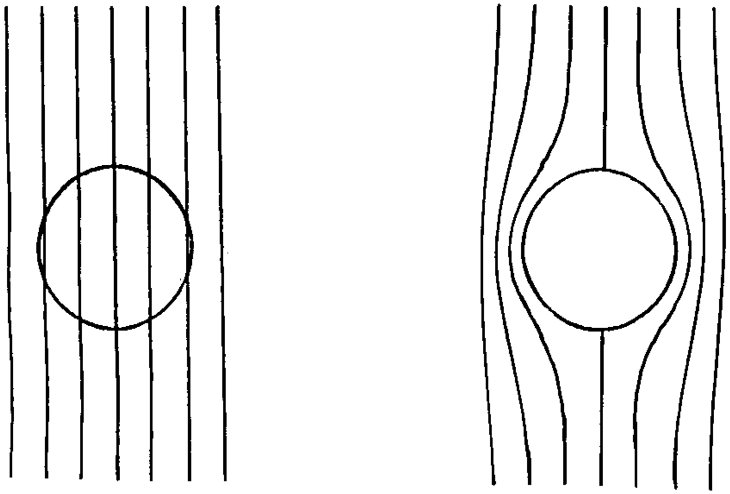
Critical Temperature T_c

$$3.5\, k_B\, T_c = 2\, \Delta(0)$$

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.

$$\frac{B_c{}^2}{2\mu_o} = G_n - G_s$$

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

$$G_n(0) - G_s(0) = 1/2 N_F\, (\Delta(0))^2$$

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

$$\gamma = 2/3\, \pi^2\; N_F\; k_B{}^2$$

where γ is Sommerfeld coefficient of electronic specific heat

$$C = \gamma\, T + A\, T^3$$

Critical temperature and critical magnetic field

Combining the previous equations:

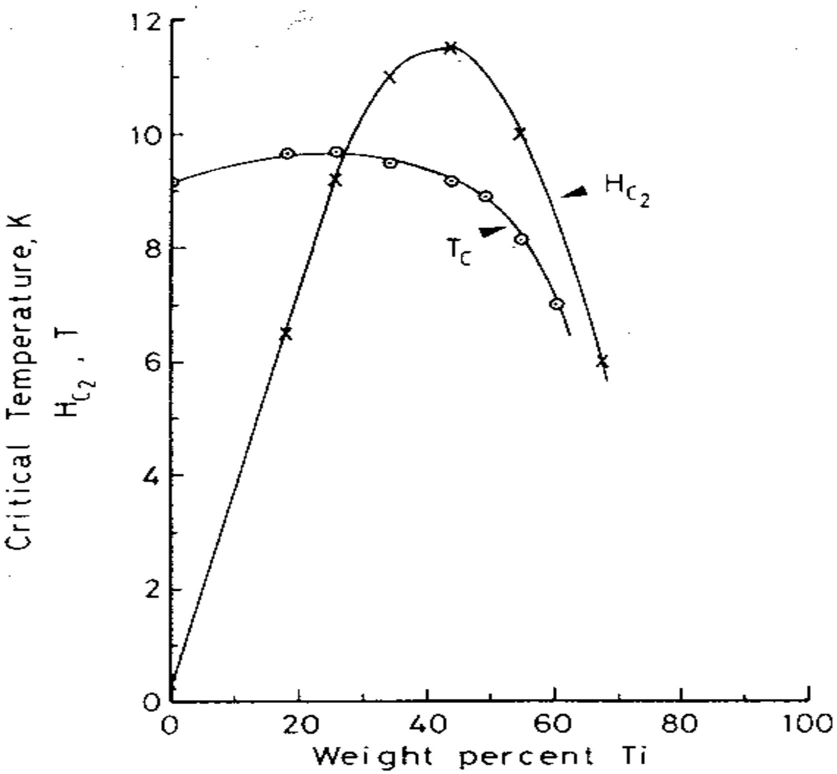
$$B_c(0) = \left\{\frac{3\mu_0}{2}\right\}^{\frac{1}{2}} \frac{3.5}{2\pi} \gamma^{\frac{1}{2}} T_c = 7.65x10^{-4} \gamma^{\frac{1}{2}} T_c$$

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 λ the London penetration depth.

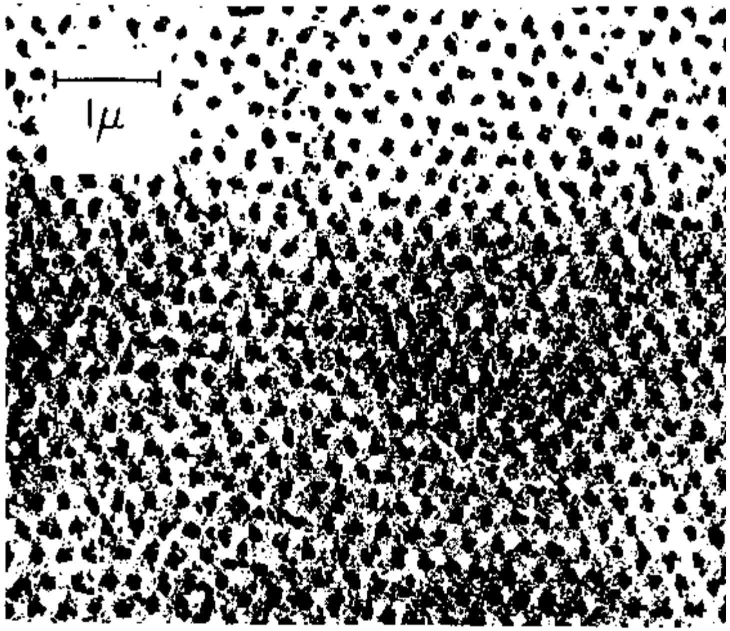
Another characteristic distance is the coherence length ζ; the minimum distance over which the electronic state can change from superconducting to normal.

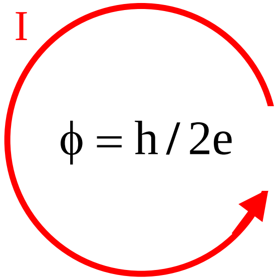
Critical properties of type II superconductors

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





a single fluxoid encloses flux

$$\phi_o = \frac{h}{2e} = 2\times10^{-15}\,Webers$$

where h = Planck's constant,
e = electronic charge

upper
critical field

$$B_{c2} = \sqrt{2}\kappa B_c$$

in the 'dirty limit'

$$\kappa \approx 2.4\times10^{6}\gamma^{\frac{1}{2}}\rho_n$$

where ρ_n is the normal state resistivity

! best superconductors are best resistors !

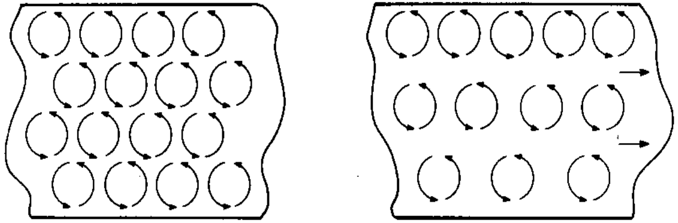
thus the upper critical field:

$$B_{c2} = 3.1\times10^{3}\,\gamma\,\rho_n\,T_c$$

for NbTi: γ ~ 900 J m^{-3} K^{-2} ρ_n ~ 65 x10^{-8} Ω m T_c = 9. K hence B_{c2} = 18.5 T

Critical current density

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



spacing between the flux lines

$$d = \left\{ \frac{2}{\sqrt{3}} \frac{\phi_o}{B} \right\}^{\frac{1}{2}} \quad = 22nm \quad at\ 5T$$

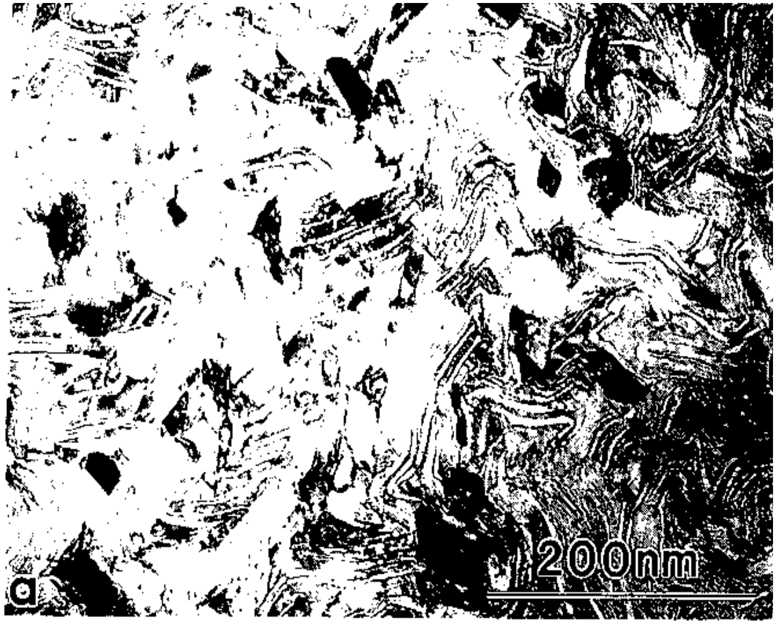
a uniform distribution of flux lines gives no net current, so $J_c = 0$,

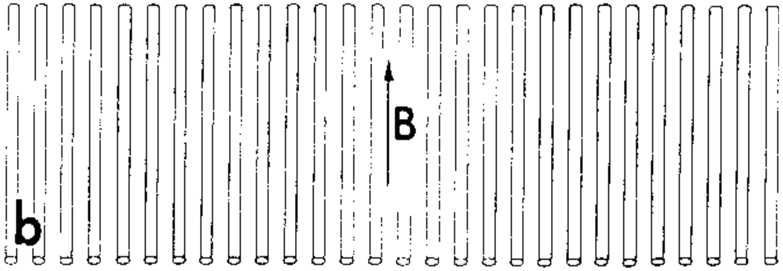
but a gradient produces a net current density

$$\nabla x B = \mu_o \ J = J_c$$

- 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 α Ti in NbTi

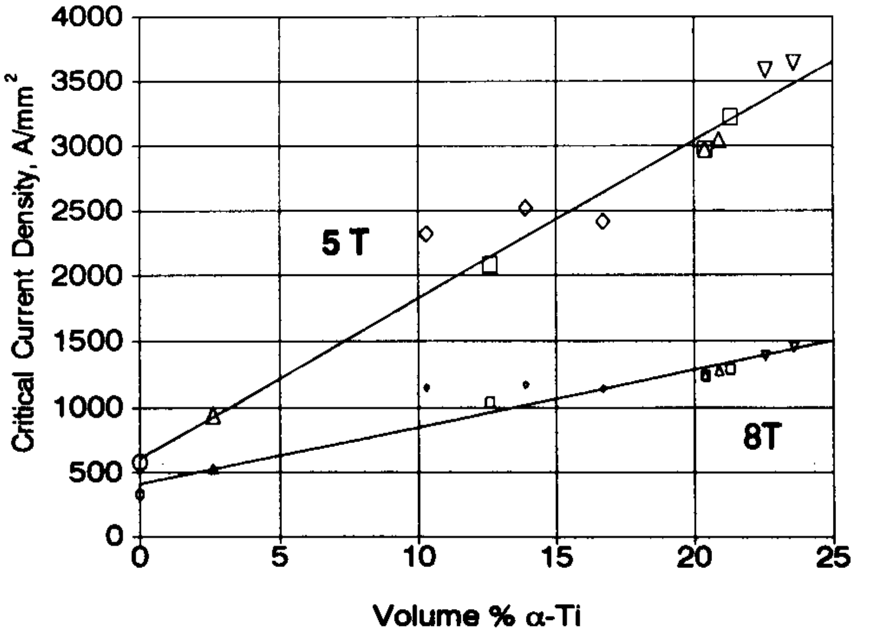


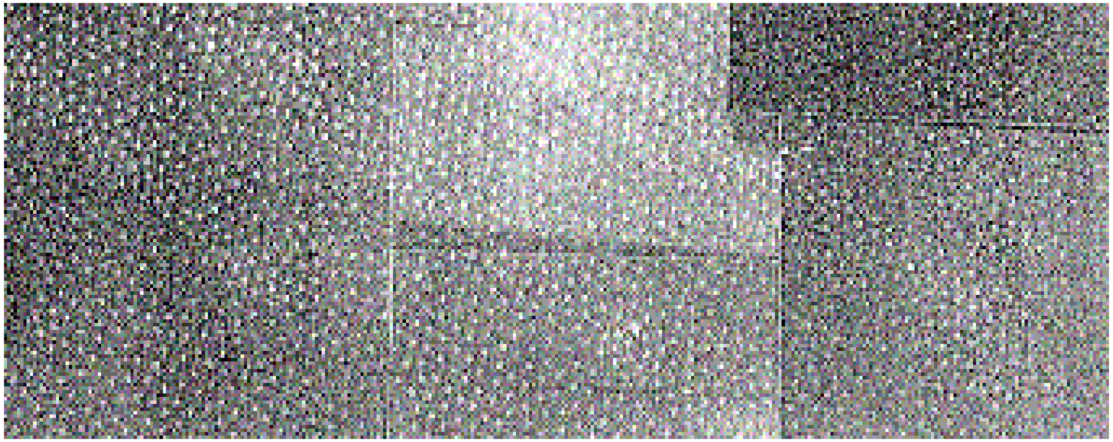


Flux lines lattice at 5 T on the same scale.

Critical properties summary

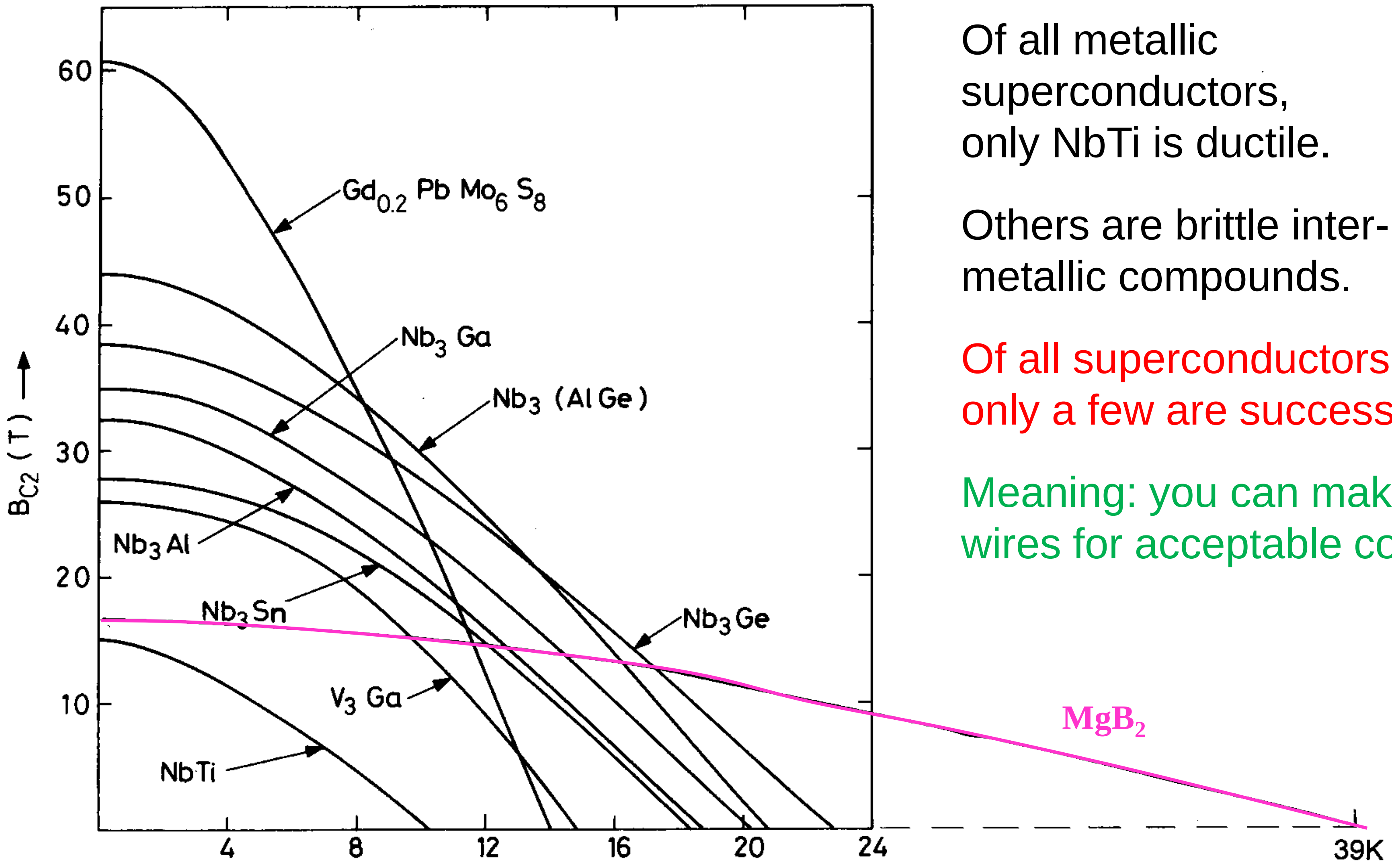
- Critical temperature: choose the right material to have a large energy gap or 'depairing energy'.
- Critical magnetic field**:** choose a Type II superconductor with a high critical temperature and a high normal state resistivity.
- Critical current density: mess up the microstructure by cold working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





Similar effects in high temperature superconducting materials: flux line lattice in BSCCO.

Upper critical magnetic field of metallic superconductors



Critical temperature [K]

Of all metallic superconductors, only NbTi is ductile.

Others are brittle inter-metallic compounds.

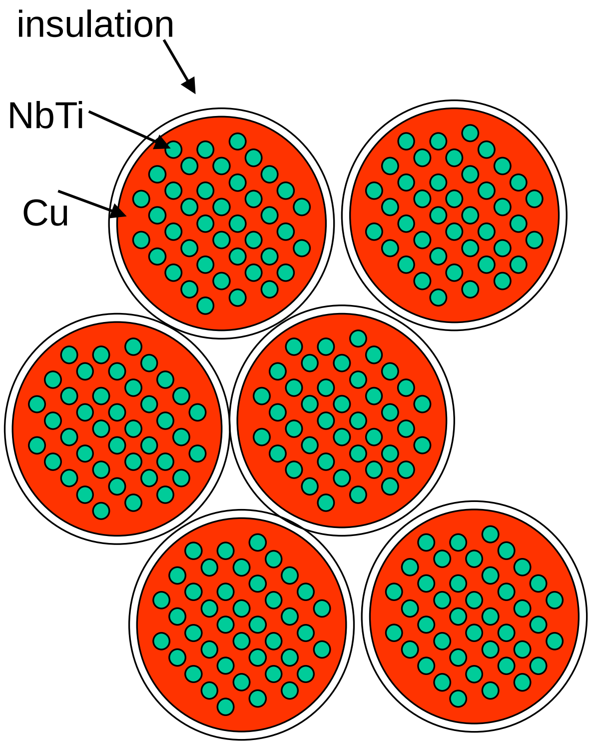
Of all superconductors, only a few are successful !

Meaning: you can make a wires for acceptable cost.

Engineering current density

In designing a magnet, what really matters is the overall engineering current density J_{eng}

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



fill factor in the wire: $$\lambda_{sc} = \frac{1}{(1+\lambda)}$$

where λ = area ratio of matrix to superconductor

typically:

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

for Nb_3Sn $\lambda \sim 3.0$ → $\lambda_{sc} \sim 0.25$

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

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

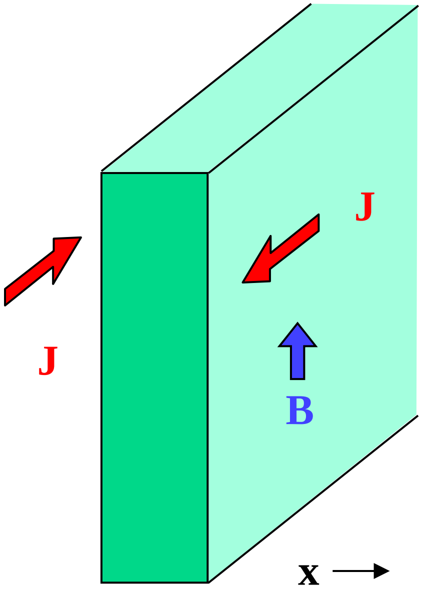
So typically $\boldsymbol{J_{eng}}$ is only 15% to 30% of $\boldsymbol{J_{supercon}}$

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

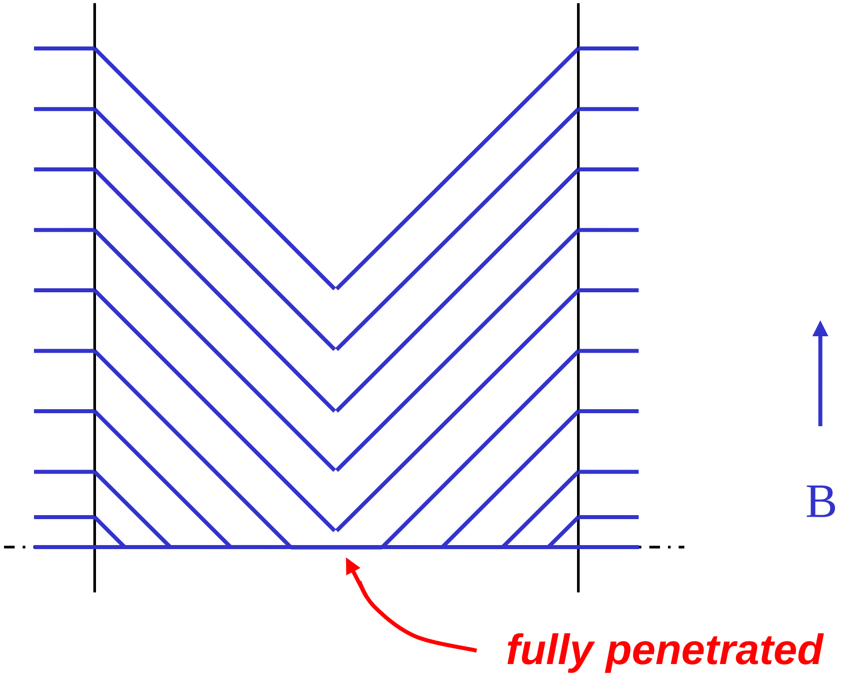
$$\frac{\partial B_y}{\partial x} = -\mu_o J_z = \mu_o J_c$$

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

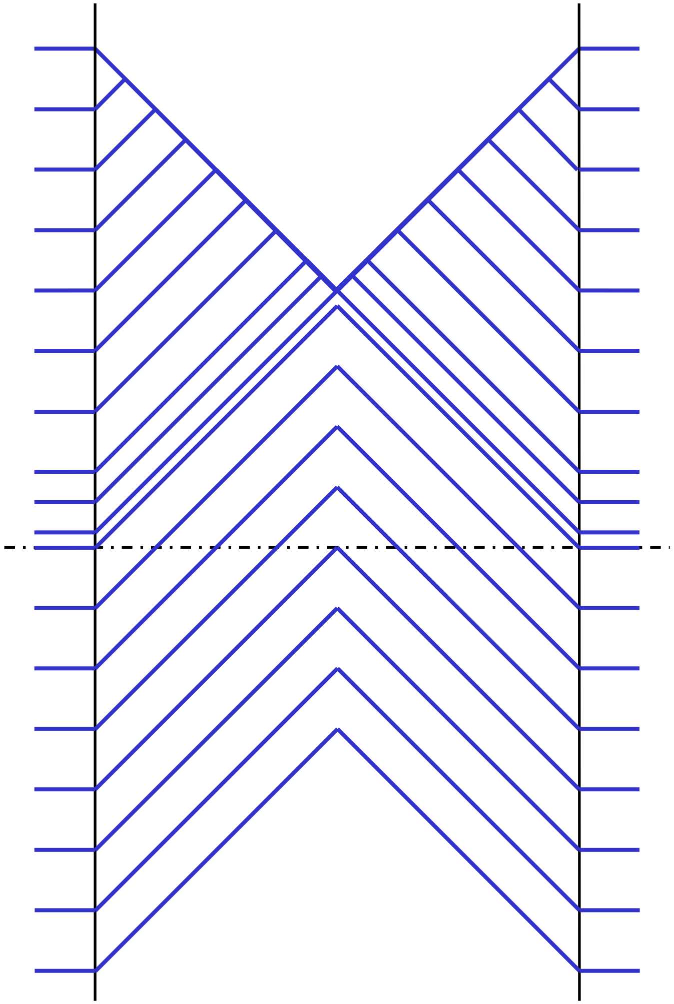
Everywhere in the superconductor the current density is either J_c or zero.

The flux penetration process

plot field profile across the slab



field increasing from zero

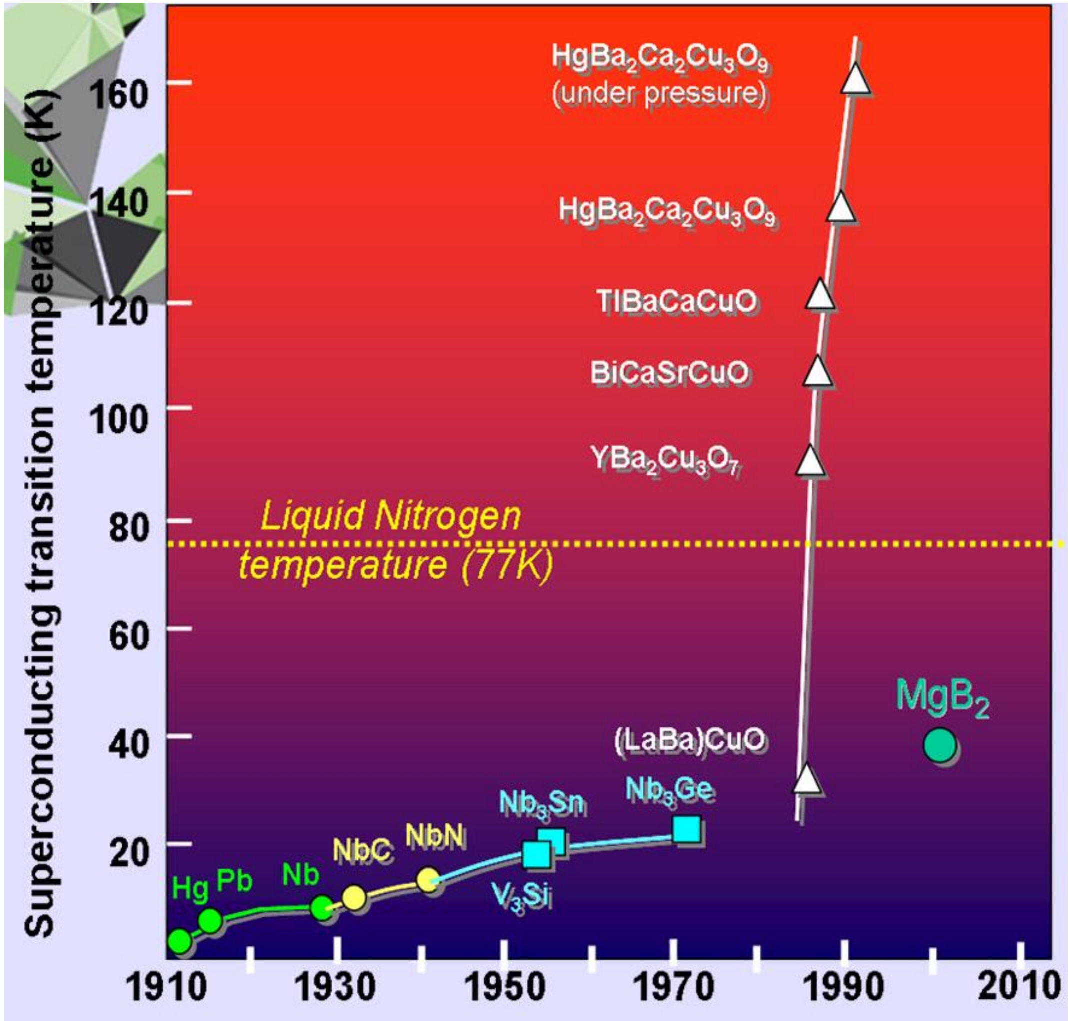


field decreasing through zero

Conclusion for basic properties

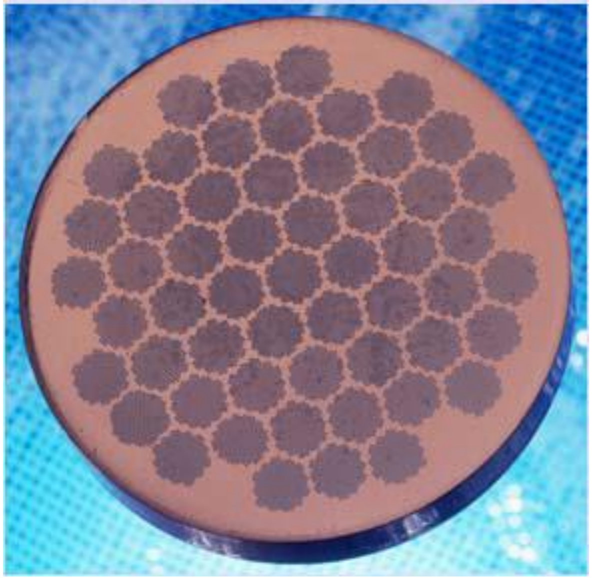
- Superconducting magnets do not use power (dc), but need to be cooled.
- They produce high magnetic fields - but in changing fields they suffer ac loss.
- Two types of superconductor
  - type I: not suitable for high field
  - type II: good for high field - but must work hard to get current density.
- 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 T 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



History of superconductors inventions

Cubic alloy, isotropic

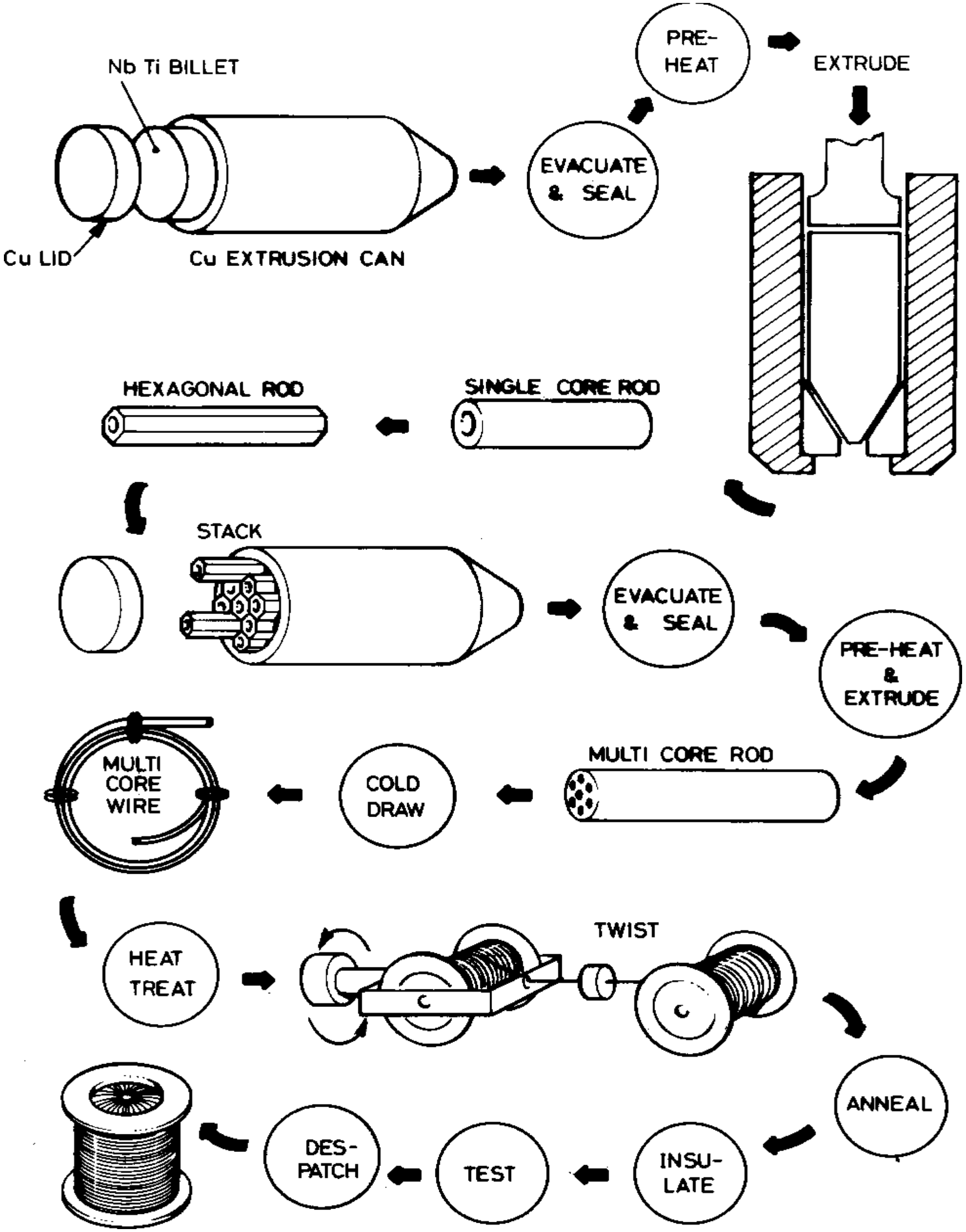


Tc :   11 K
Bc2 : 13 T

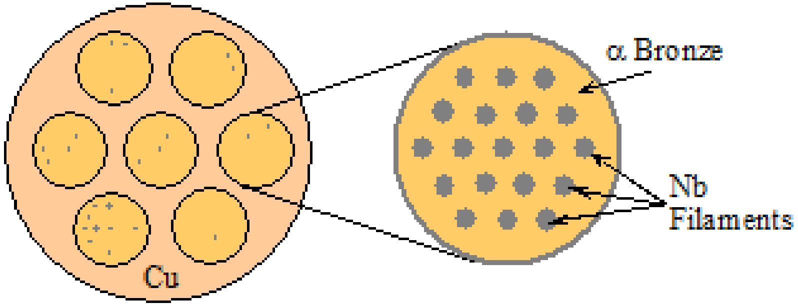
Very well developed
~1 € / kA m

Manufacturing NbTi wires

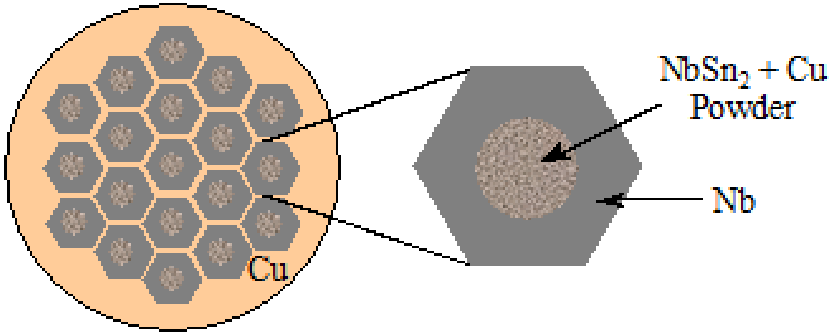
- Vacuum melting of NbTi billets
- Hot extrusion of the copper NbTi composite
- Sequence of cold drawing and intermediate heat treatments to precipitate α-Ti phases as flux pinning centres
- For very fine filaments, must avoid the formation of brittle CuTi intermetallic compounds during heat treatment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



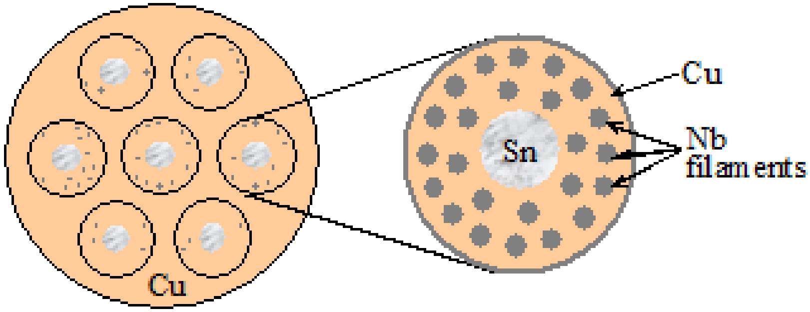
2.2 Nb_3Sn wires, 3 routes to make it



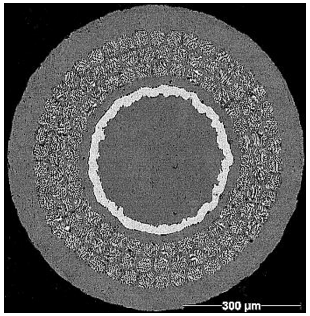
Bronze Process



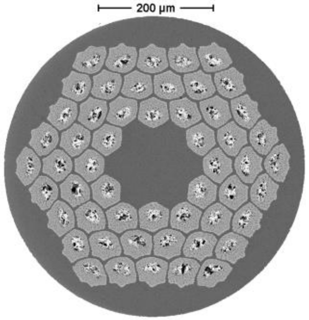
Powder-in-tube Process



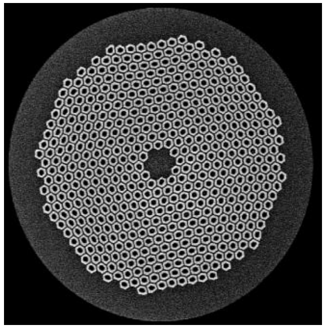
Internal Sn Process



Bronze Route, Bruker EAS

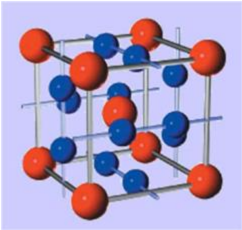


Internal Tin, Oxford OST



$NbSn_2$ Powder in Tube, Bruker EAS

T_c : 18 K
B_{c2} : 30 T



Cubic
inter-metallic, isotropic

~ 1000 A/mm^2 (bronze)
~ 3000 A/mm^2 (IT/PIT)
at 12T and 4.2 K

Well developed,
still improving

~ 5-25 €/kA m

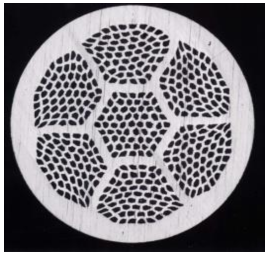
All Nb_3Sn by thermal diffusion of Sn to Nb after coil winding.

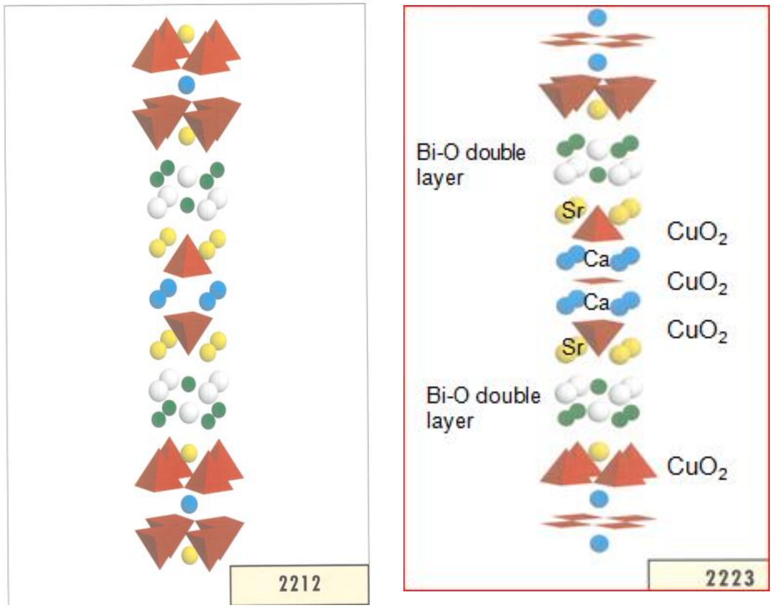
2.3 BSCCO and YBCO

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

B2223: Tc ~108 K, tape, no wire! R&D support halted except in Japan.

B2212: Tc ~ 92 K and can be made as wire ! Modest investments to further develop, mainly by Oxford-OST.

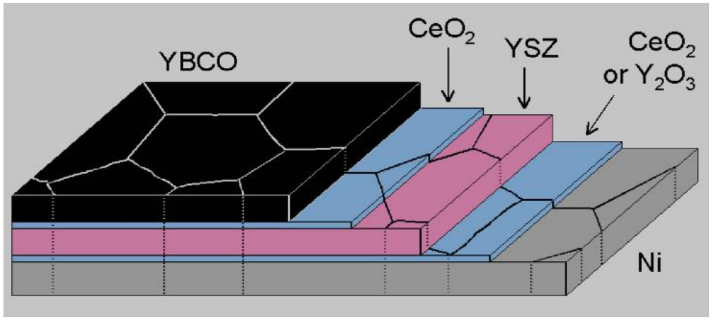




Orthorhombic oxide; strongly anisotropic

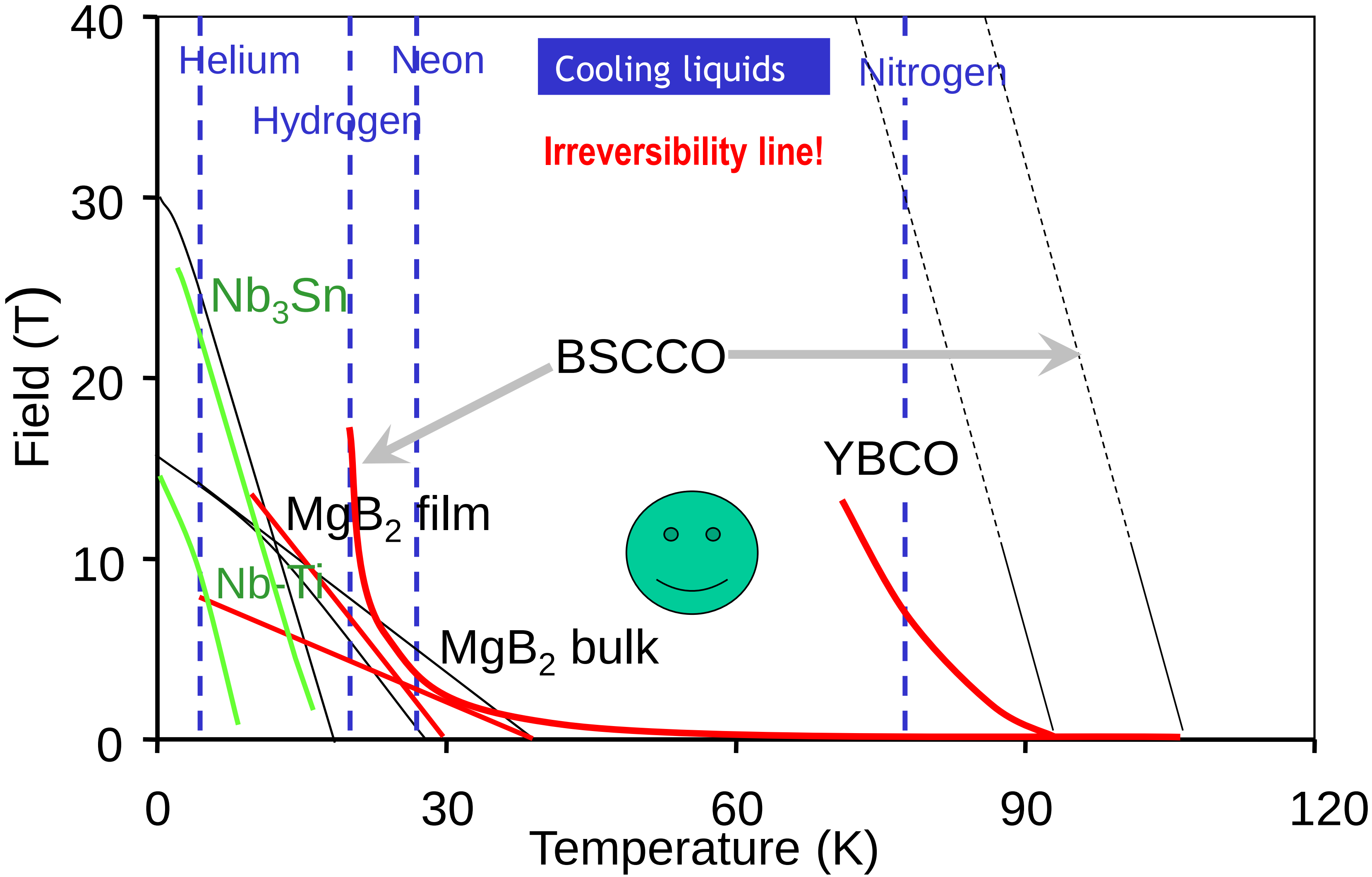
Generation II: Coated YBCO conductor Y-Ba-Cu-O (Y-123)

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



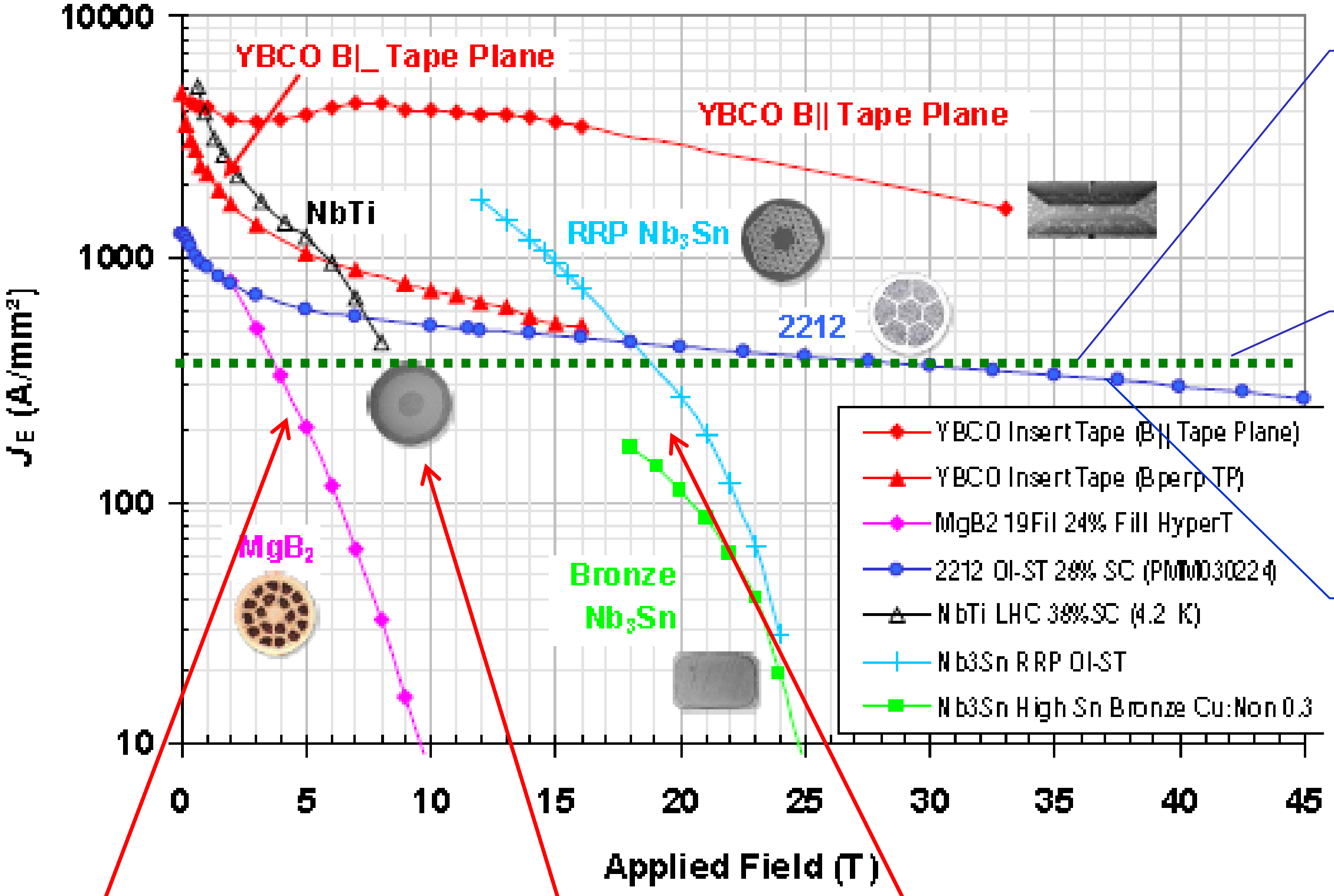
~ 100-300 €/kA m !

B versus T of superconductors, unique Y123 domain



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 !

Minimum practical current density

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

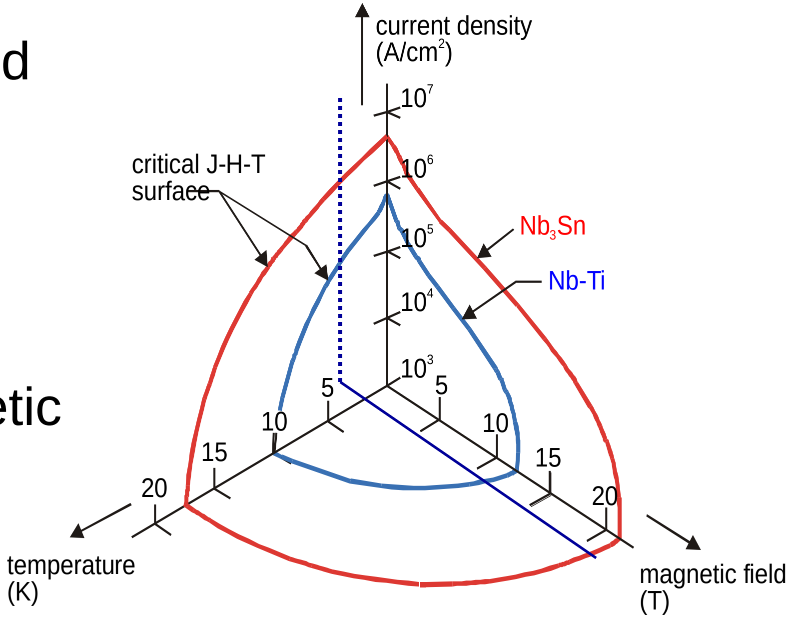
Nb_3Sn
for any magnets of 9-20T

B2212 or Y123
for DC magnets of 17-40T provided cost comes down drastically

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

$B_{c2}(T) = B_{c2}(0)\,[1 - (T/9.2)^{1.7}]$ $B_{c2}(4.2K) = 10.7$ T

$T_c(B) = Tc(0)\,(1 - (B/14.5))^{0.59}$ $T_c(5T) = 7.16$ K

Similar relations are found for Nb_3Sn and BSCCO 2212 and 2223.

Temperature margin

When a transport current flows, the onset of resistance is

is further reduced from T_c to T_{cs}, the current sharing temperature

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

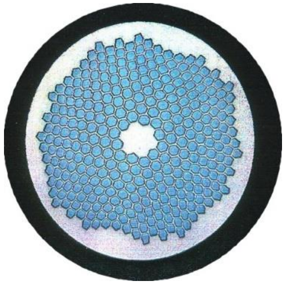
- So we lost a lot of margin from 9.2 K → 7.2 K → 5.7 K versus 4.4 K.
- At 4.4 K, at 50% I_c and 5 T there is only 1.2 K margin !
- At 75% of I_c we get 0.7 K, so we never can operate very near to I_c !
- Following $\Delta T = Q / c(T)$

  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 .

Effects of disturbances, sources of heat

We can distinguish various sources of heat



Heat pulses, transients

- Flux jumps
- Cracking of resin
- Wire motion; load in μJ/mm^3

Continuous heating

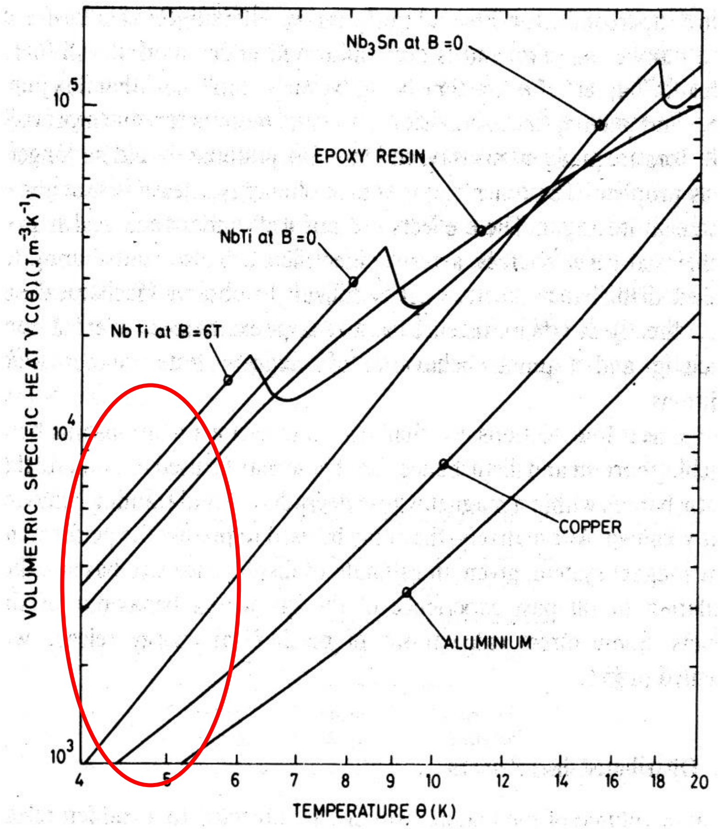
- Flux flow
- Losses in pulsed magnets and at fast ramp down
- AC losses at 50Hz, energy applications, due to alternating current and fields
- Current sharing due to bad sections in the conductor
- Joints between superconductors, usually < n Ω, no problem
- Synchrotron radiation in accelerators
- Neutron 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:

  $C_p(T) = \eta((6.8/\eta + 43.8)T^3 + (97.4 + 69.8\,B)T)$ μJ/mm^{3}K, which is at 5 T and 40% NbTi in Cu matrix:
- 2.5 μJ/mm^{3}K at 4.2 K and
- 0.5 μJ/mm^{3}K at 1.9 K !
- 2.5 μJ/mm corresponds to a movement in a 1 mm wire at 5 T and 500 A of 1 μm only!



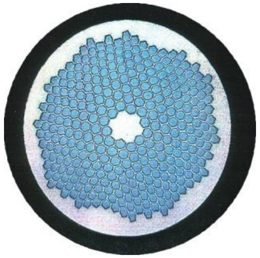
Heat release of μJ/mm^3 has to be avoided, otherwise magnet will quench

- 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 a various wires

- In a bare NbTi wire or filament:
  take 5 T; 3000 A/mm^2; ρ= 6x10^{-7} Ωm; λ= 0.1 W/mK; T_c= 7 K
  and we find 0.3 μm only
  in a 0.3 mm wire this requires about 1nJ 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

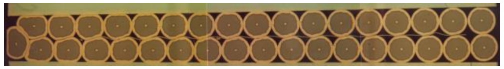


Remedy: reduce ρ by using copper matrix (3x10^{-10} Ωm, factor 2000 !)
and increase λ by using copper (> 200 W/mK, factor 2000 again !)

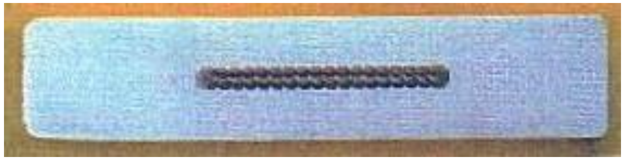
Thus we see how wonderful copper is, without copper no sc magnets !

✓ 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 !



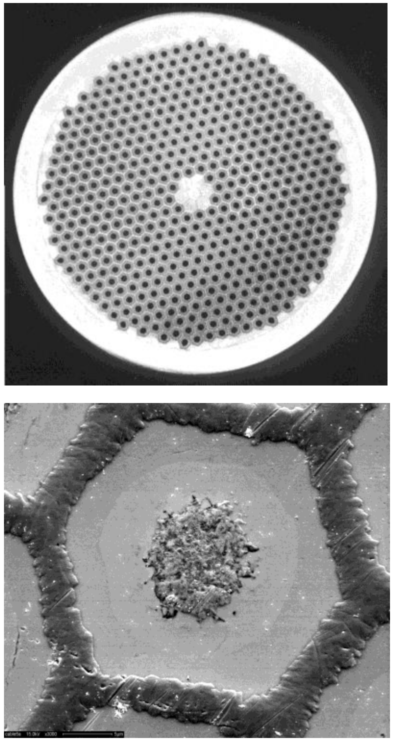
Achieve stable performance: Adiabatic Filament Stability

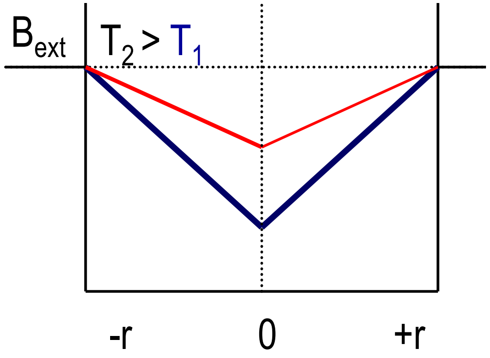
Field penetration in filaments

- 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 ΔT1 will cause a –ΔJc, so flux motion, leading to E, this leading to heat and so again a ΔT2
- When ΔT2 > ΔT1, the process will accelerate and the flux profile collapses
- Based on simple slab model, the adiabatic stability criterion is found:

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

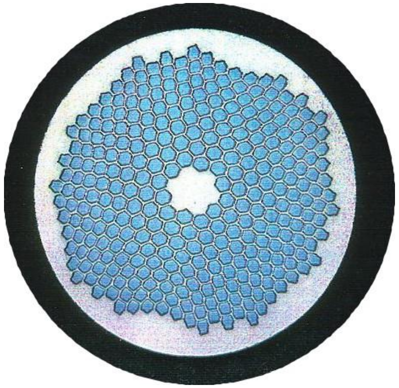
Thus we see a maximum in the filament thickness for a given current density, to guarantee stability.





Adiabatic Filament Stability

Example for NbTi



- Specific heat c = 5600 J/m^3; T_c(5T) = 7.2 K, T_o= 4.2 K and J_c = 3000 A/mm^2, we find ~70 µm.
- Filament diameter must be adapted to the Jc(B).
- Must be much smaller than 70 µm below 5T

  (AC applications, transformers).

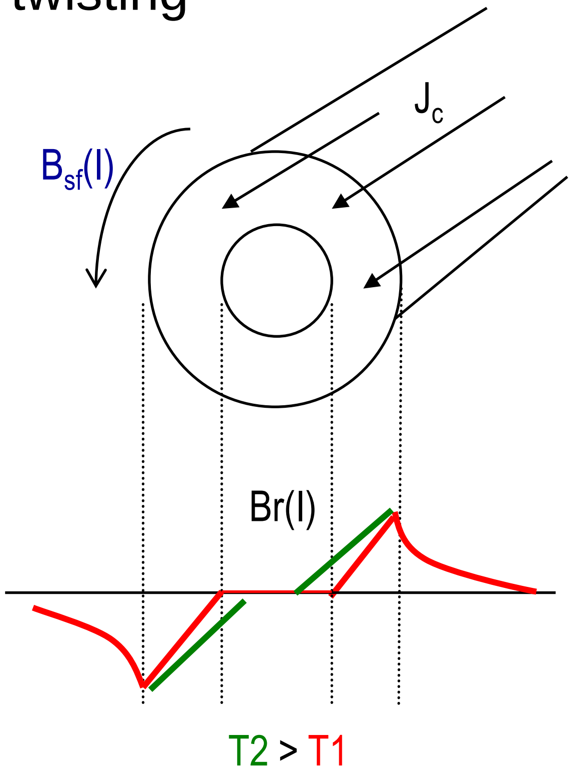
Consequences:

- Split the NbTi section required for the Ic 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 ΔT
- Field profile has to change, penetrates deeper, causing heat dissipation taken up by the enthalpy up to a certain limit
- Assuming η=sc/total ratio and current density ηJ
- We find for the adiabatic self-field criterion:



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

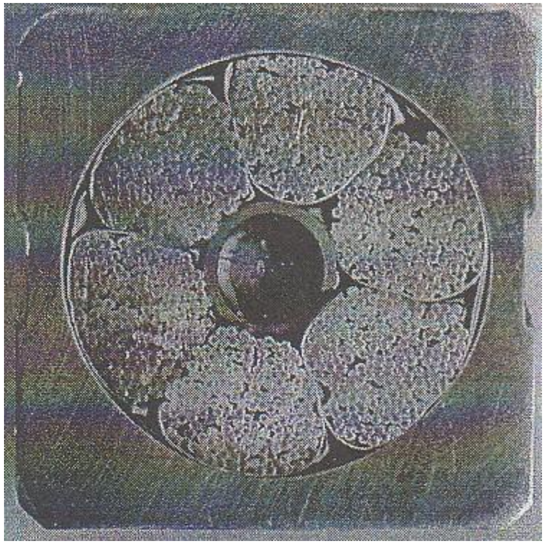
where $f\,(I/Ic) = 1/(-0.5\ \ln(I) - 3/8 + i^2/6 - i^4/8)$

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.



~1152 wires ITER Nb3Sn cable

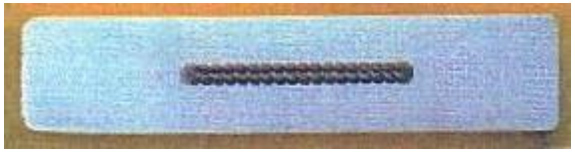
LHC type Nb3Sn Rutherford cable

- 33 stands single stage twisted.
- 13 kA at 11 T.

33 wires LHC-type Nb3Sn cable

ATLAS cable

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



40 strands ATLAS BT cable

Conclusion

Due to the very low heat capacity of materials at low temperature heat production of μJ/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)

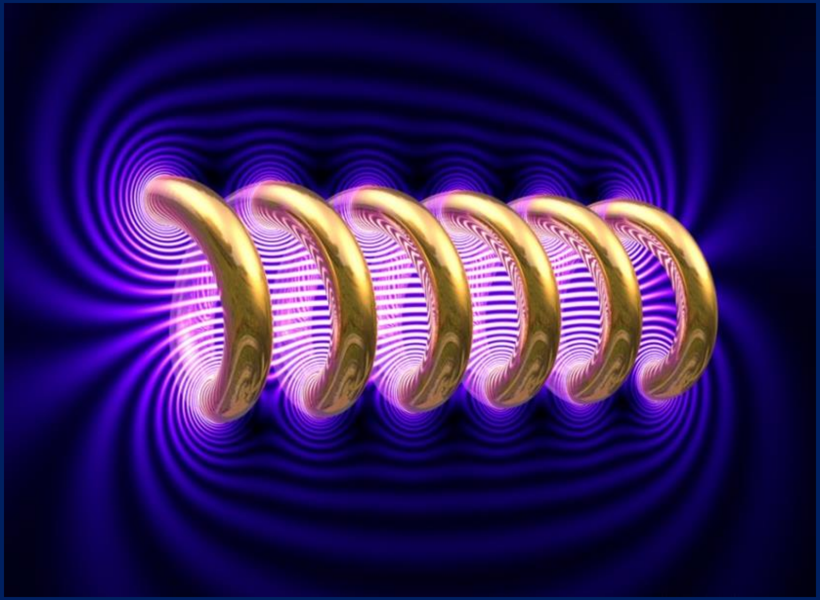
The next issue is when despite all this a quench occurs, how the magnet can be switched of safely and resume operation

Why magnets require High Current and Cables

Magnetic field and stored energy

$B \propto N.I$ $E \propto B^2.\text{Volume}$

Inductance $L \propto N^2$



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

--->Thus low N, high current I

Also $I_{safe} \propto J.E/V_d$, kV-range for V_d , with usual current densities this leads to 10-100 kA

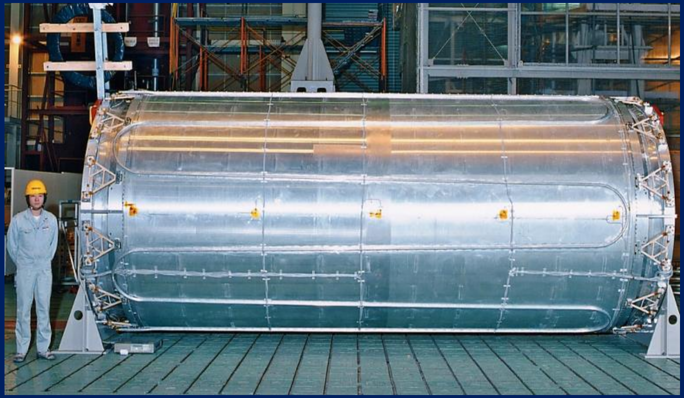
- Given strand currents of typically 100 to 500A, we need for large scale magnets multi strand cables of 20-1000 strands,

  No escape!

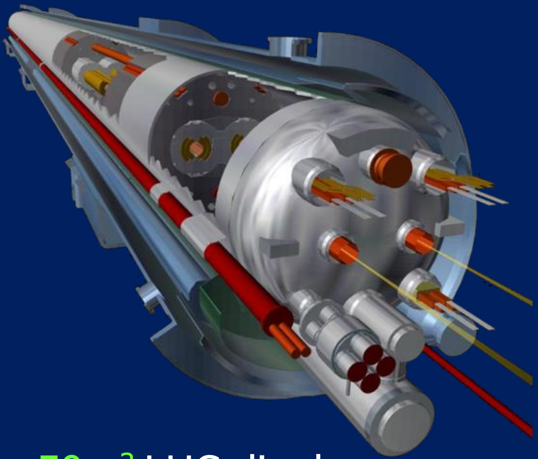
Scaling: $I_{safe} \propto J$ x B^2 x Volume

0.0001 m^3 HF insert model
~ **200 A**

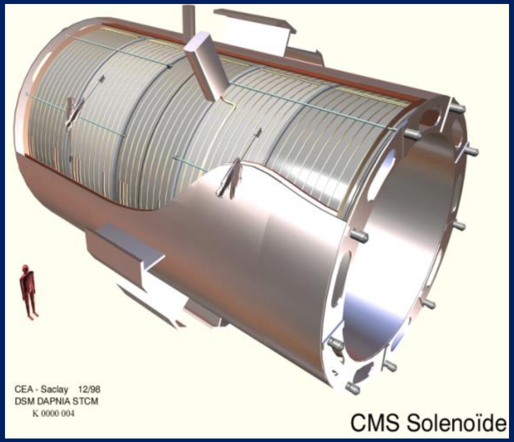
2 m^3 MRI magnet
200-800 A @ 1-3 T, ~10 MJ



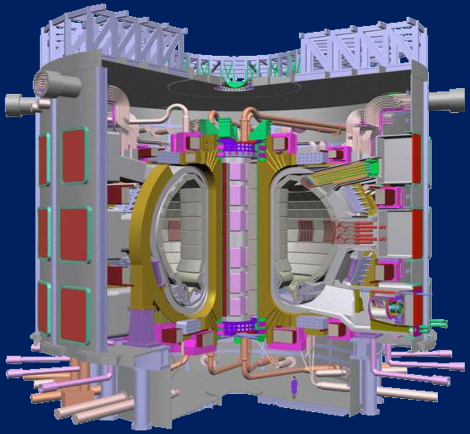
25 m^3 ATLAS solenoid
8 kA @ 2T, 40 MJ



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

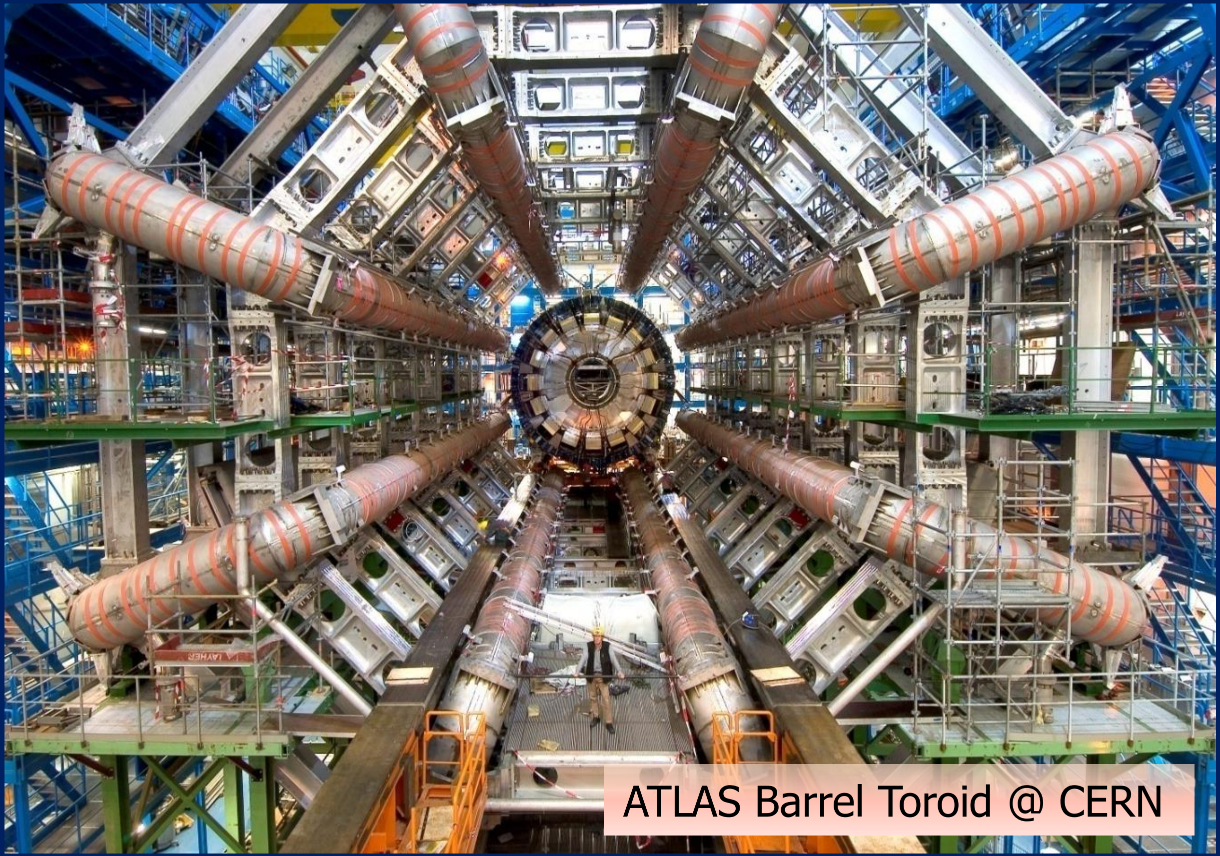
High current conductors are requested

200 A HTS tape

no

65000 A@5T Al-NbTi/Cu

yes

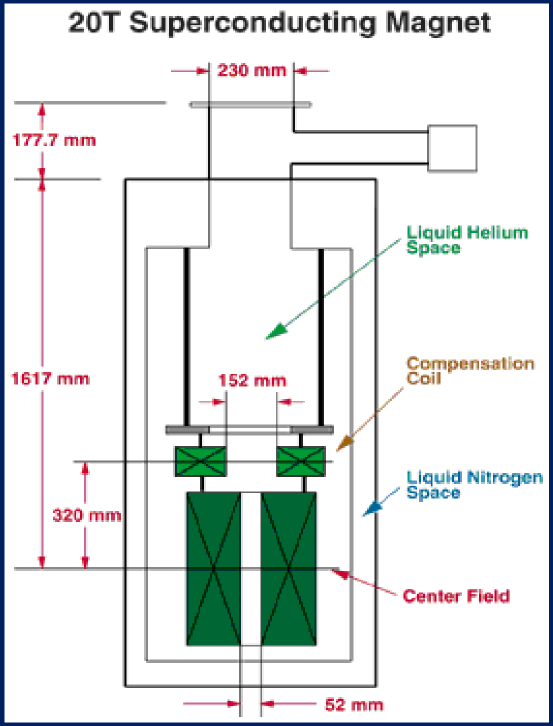


ATLAS Barrel Toroid @ CERN

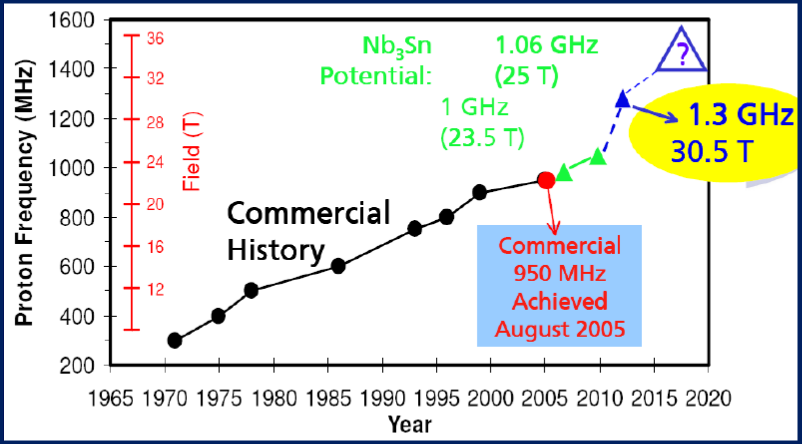
One cannot build large scale magnets from single $NbTi-Nb_3Sn-B2212-Y123$ wires or tapes

We need superconductors that can be cabled and survive a quench!

Application 1 : Lab magnets and NMR



- 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

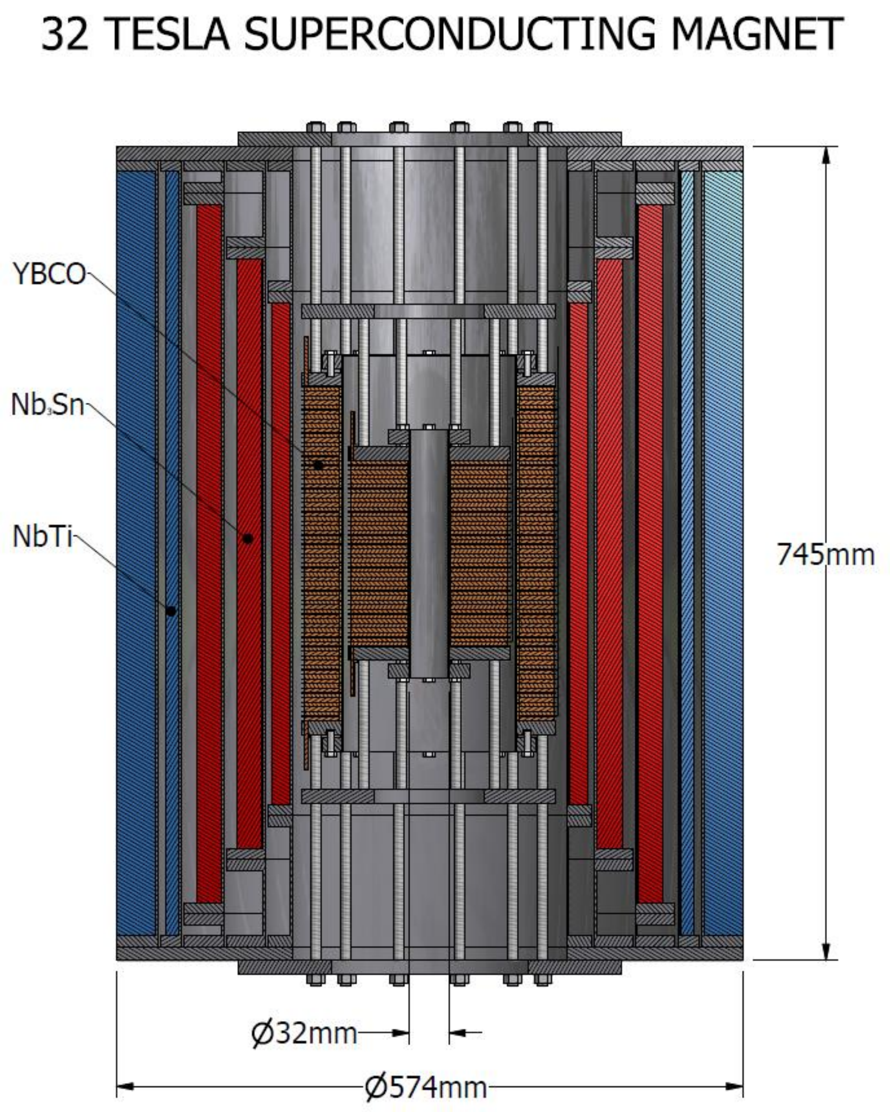
Beyond 20 T systems become too expensive for single labs and we move to user facilities

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

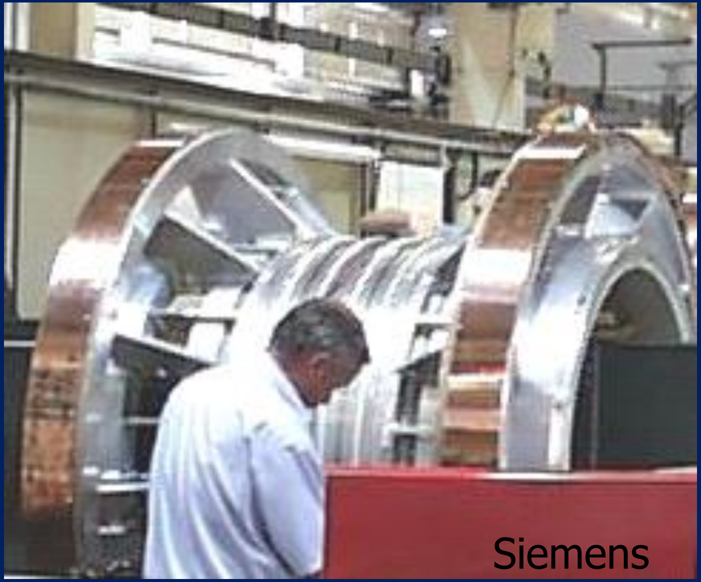
- 172 A, 619 H, 9 MJ
- Under Construction at the NHMFL, test in 2013

✓ When successful, a real breakthrough



Courtesy of NHMFL-Tallahassee

Application 2 : Magnetic Resonance Imaging



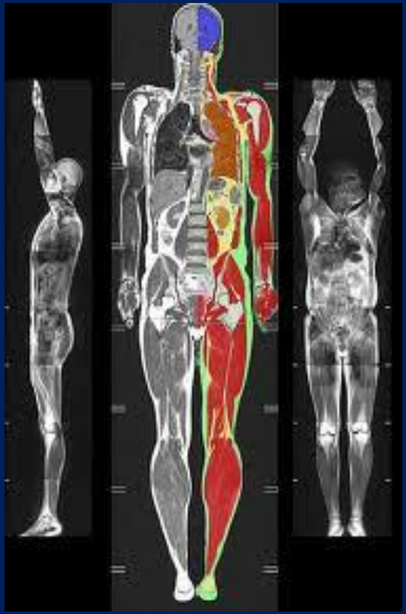
Medical NMR, MRI for diagnostics ~ 40000 units installed

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

Julich Research Center 2009

11.75 T MRI magnet

at the limit of NbTi at 1.8 K

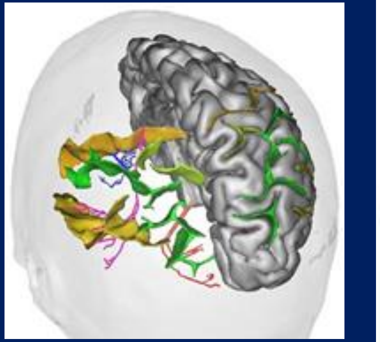
90 cm bore,

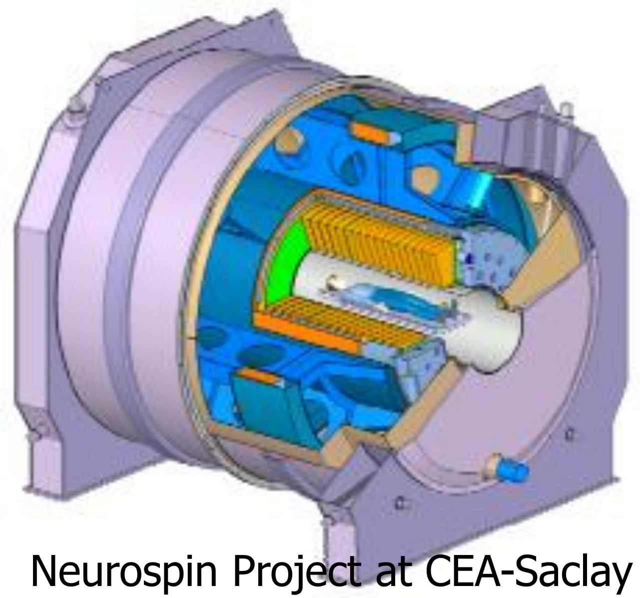
1.48 kA, 338 MJ

5.2 x 5 foot print, 132 tons

Study of central nervous systems "from mice to humans"

Stretching MRI to the limits….





Neurospin Project at CEA-Saclay

3 : Proton Therapy

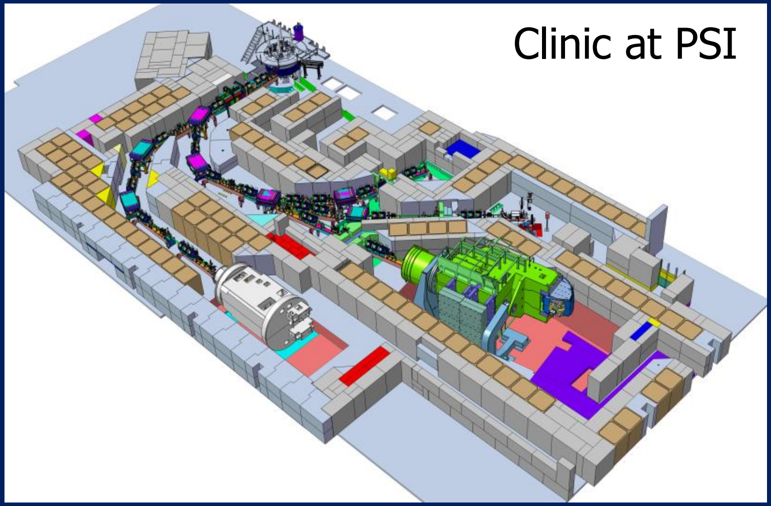
Medical accelerators providing a p beam for tumor treatment

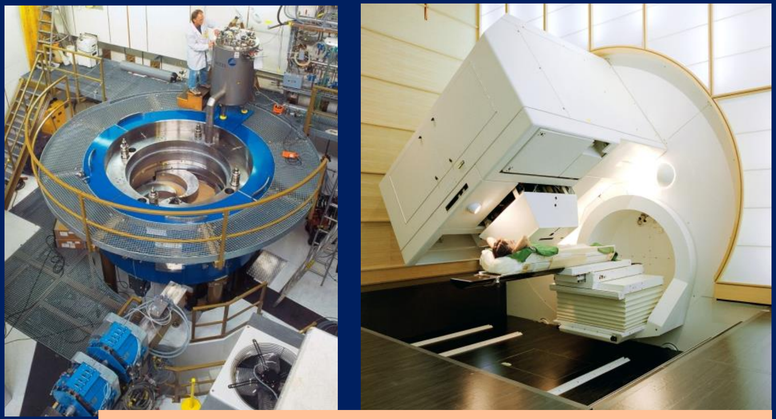
- 28 p-therapy centers in the world
- 8 operational/planned in Europe

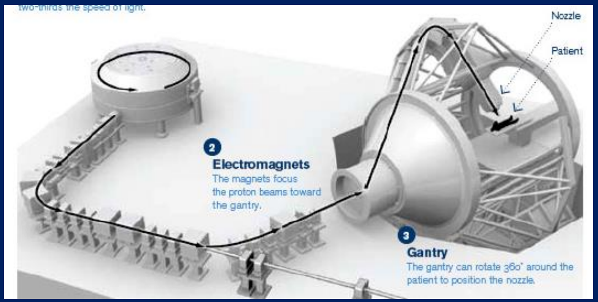
2 Options:

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

Quest for high-field compact and cost efficient integrated units


Clinic at PSI


Example PSI Switzerland, Comet synchrotron 250 MeV




Still River

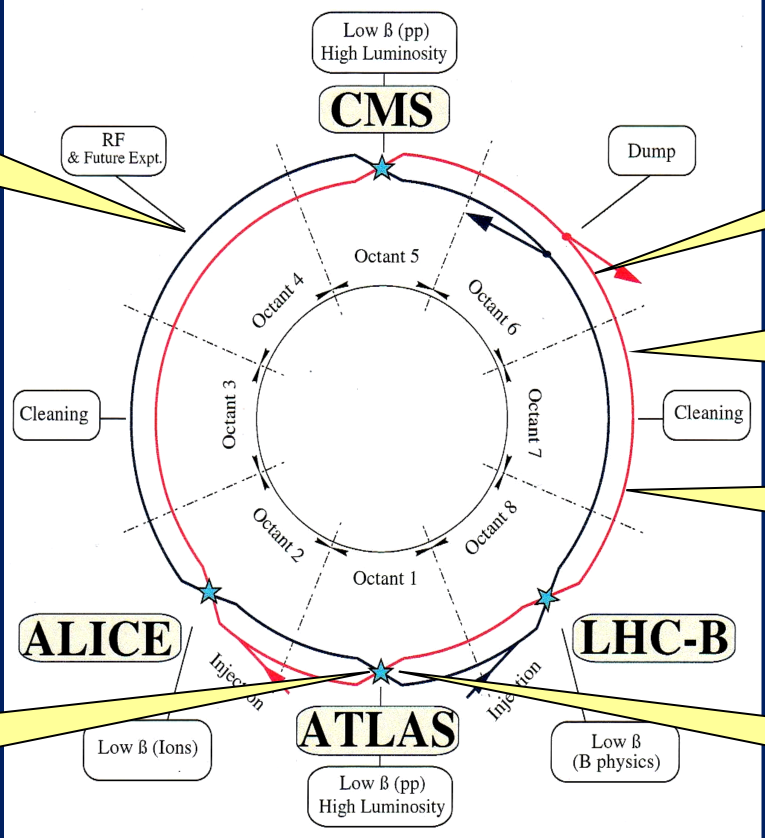
Needs some time but could become the 2nd large scale medical magnet application of superconductivity

4 : Large Hadron Collider

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



Nb/Cu cavities for acceleration

1232 dipoles magnets for bending

386 quadrupole magnets for focusing

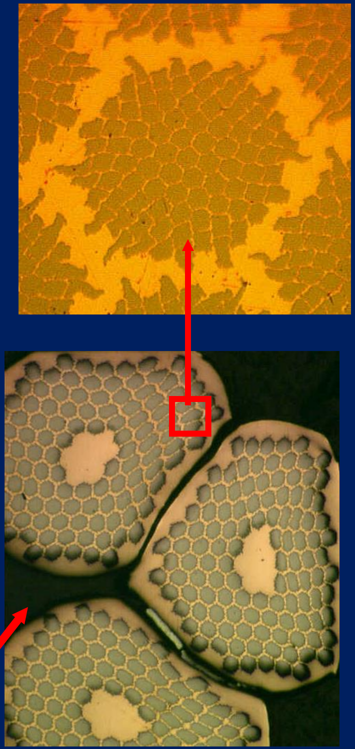
~6000 correction magnets

ATLAS and CMS detector magnets

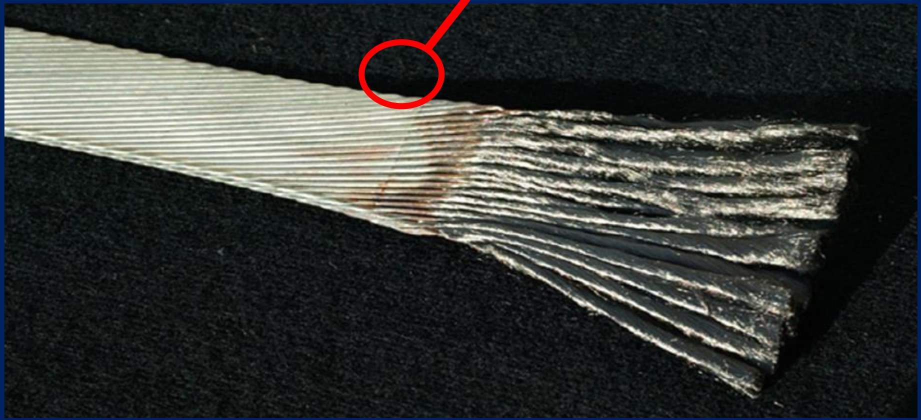
Insertion and Final Focusing magnets

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



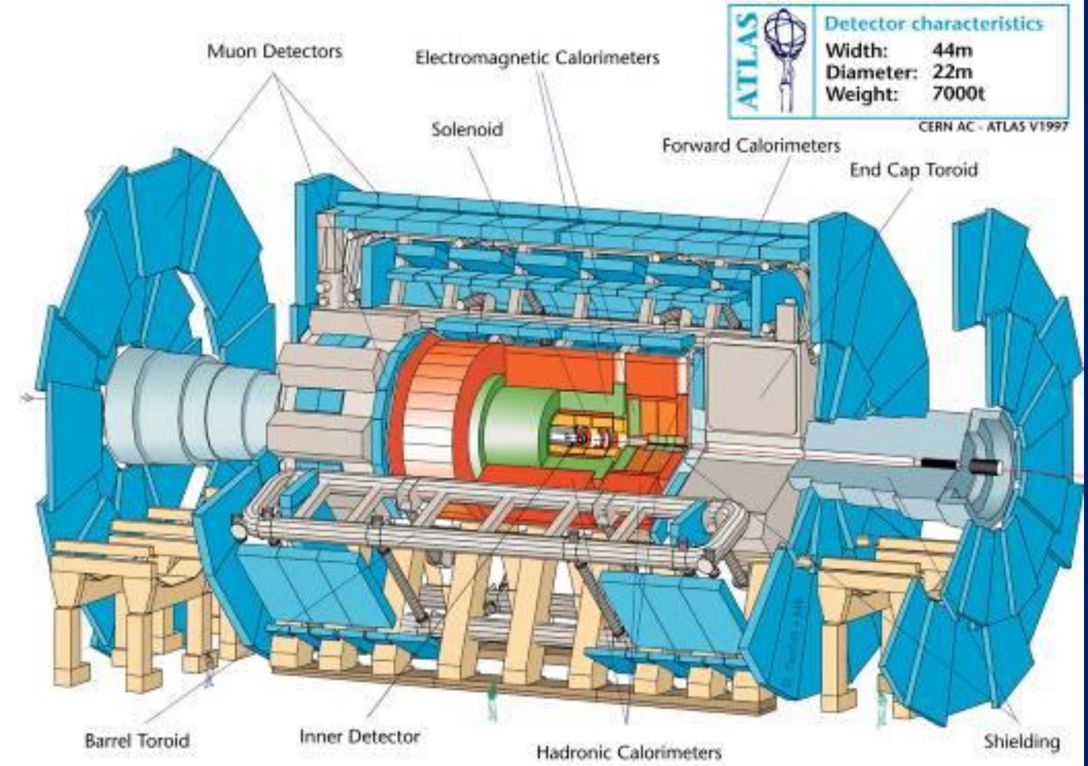
5 : HEF Detector magnets, ATLAS

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

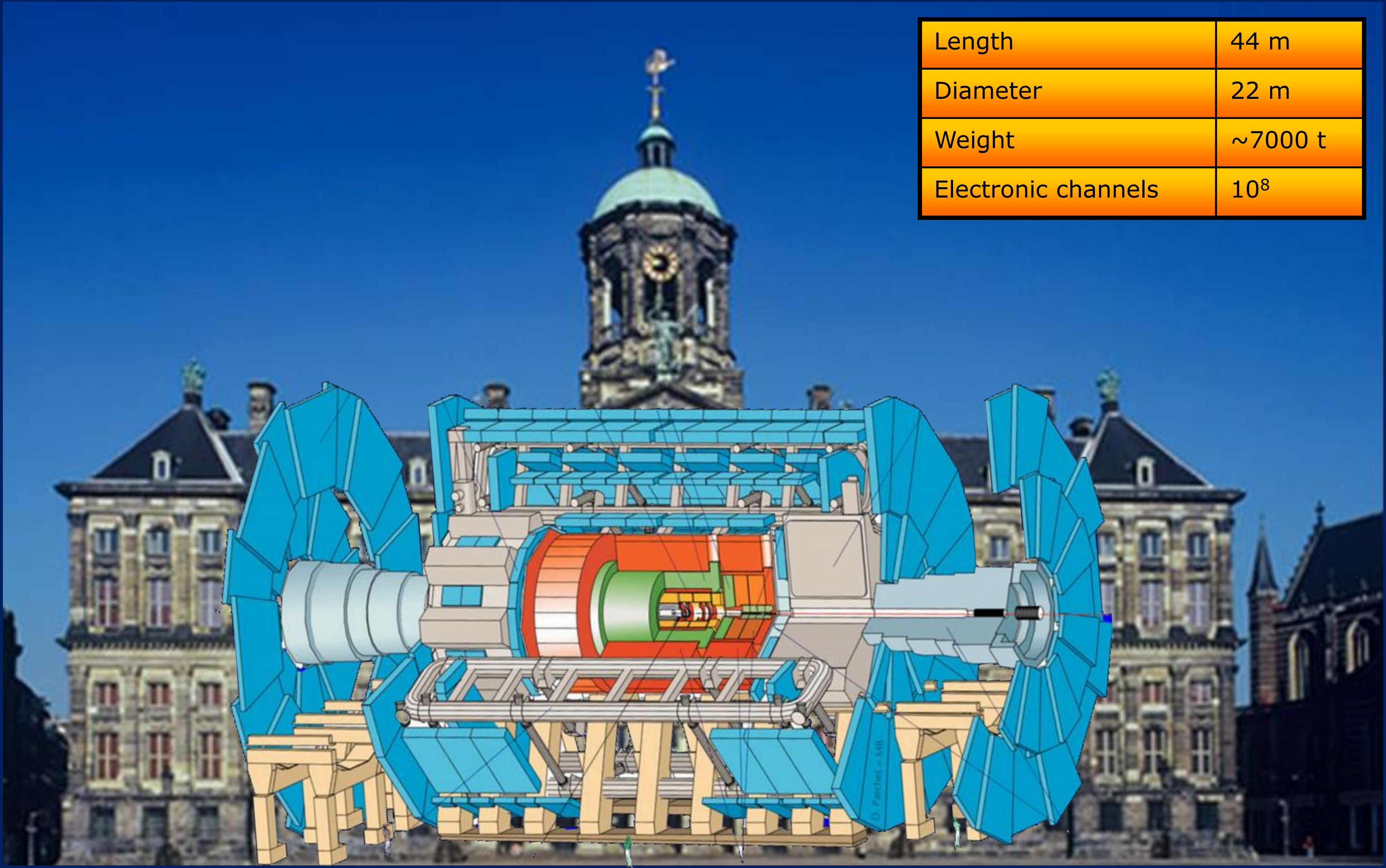


10 yrs of construction 97-07

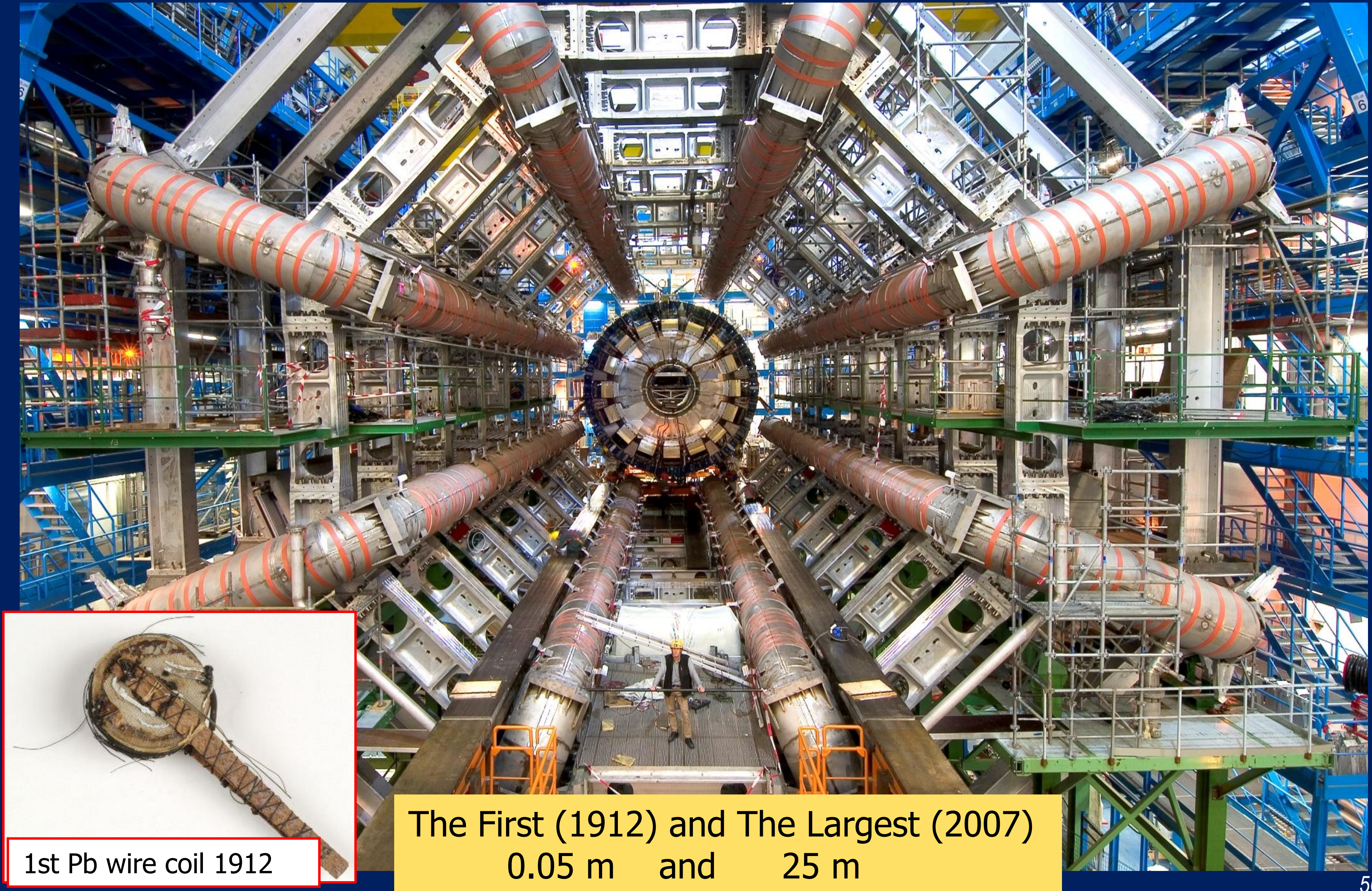
The largest trio of toroids ever built

ATLAS in Amsterdam

Length	44 m
Diameter	22 m
Weight	~7000 t
Electronic channels	10^8



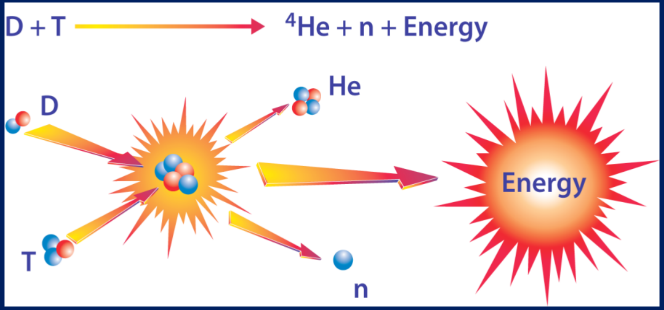
The First and The Largest



1st Pb wire coil 1912

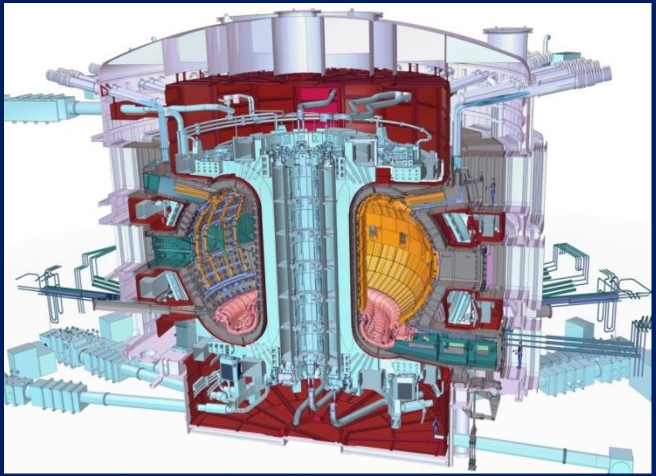
The First (1912) and The Largest (2007)
0.05 m and 25 m

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:

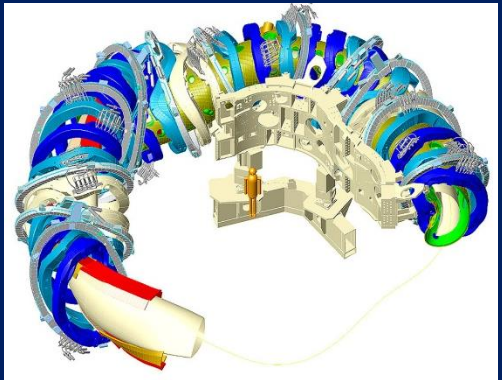
- KSTAR-Korea, EAST-China, SST1-India

2 under construction:

- JT60SA and ITER

and

- 1 Wendelstein type W7X



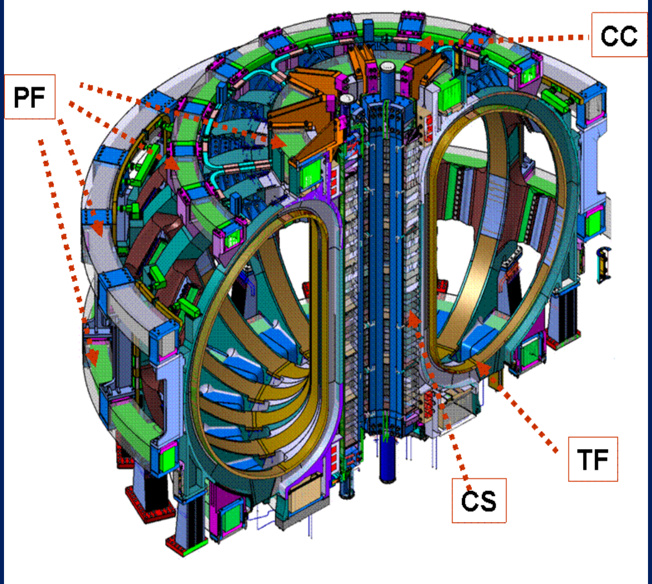
ITER magnet system

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_3Sn, no options
DEMO design start soon, still NbTi & Nb_3Sn

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

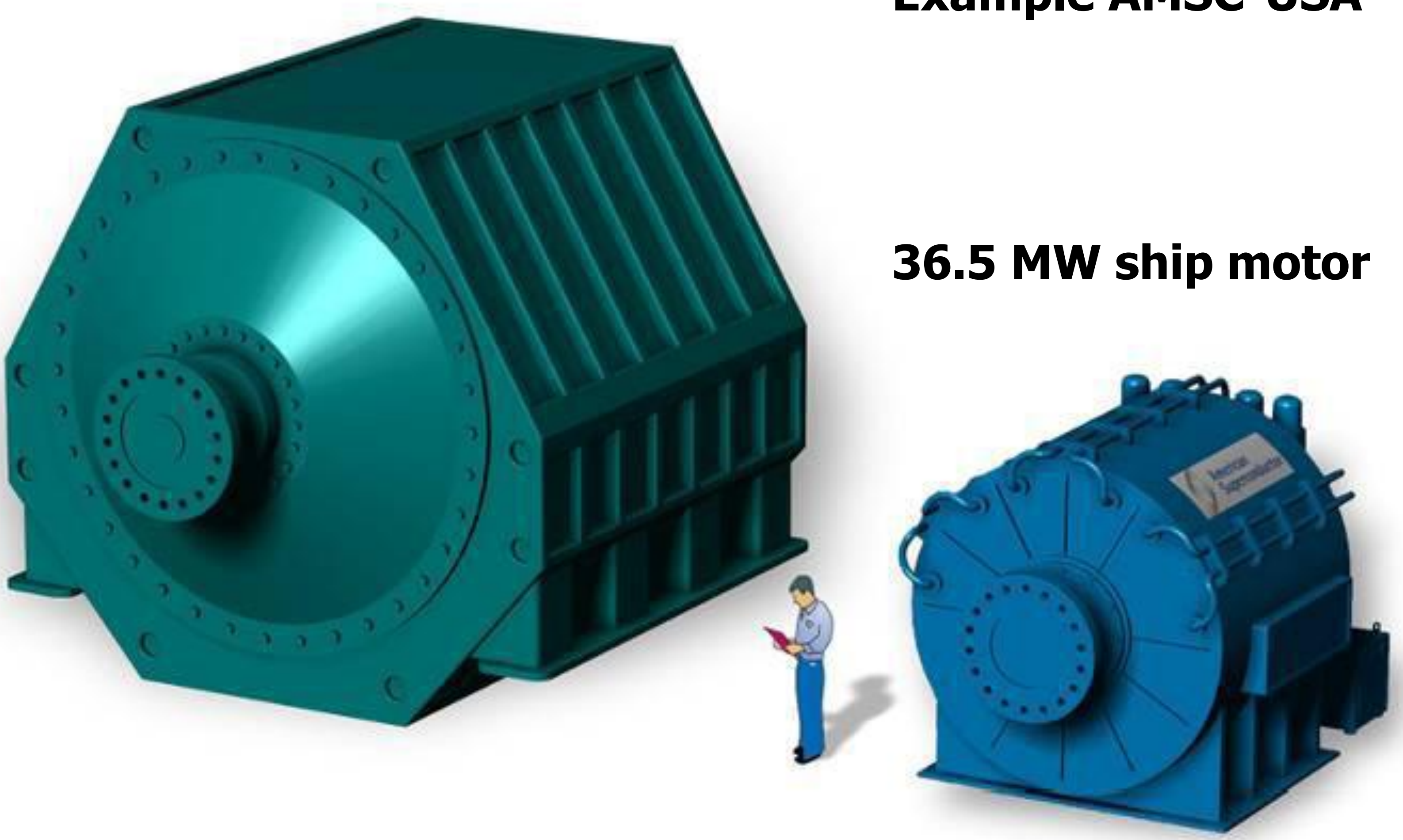


System	Energy GJ	Peak Field	Total MAT	Cond length km	Total weight t
Toroidal Field TF	41	11.8	164	82.2	6540
Central Solenoid	6.4	13.0	147	35.6	974
Poloidal Field PF	4	6.0	58.2	61.4	2163
Correction Coils CC	-	4.2	3.6	8.2	85

7 : Motors and Generators with HTS windings

Example AMSC-USA

36.5 MW ship motor



Conventional 280 t **Superconducting 75 t**

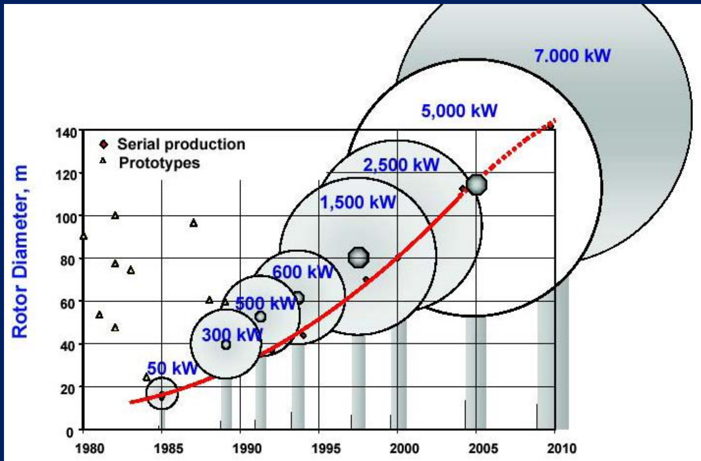
SC generators for wind turbines

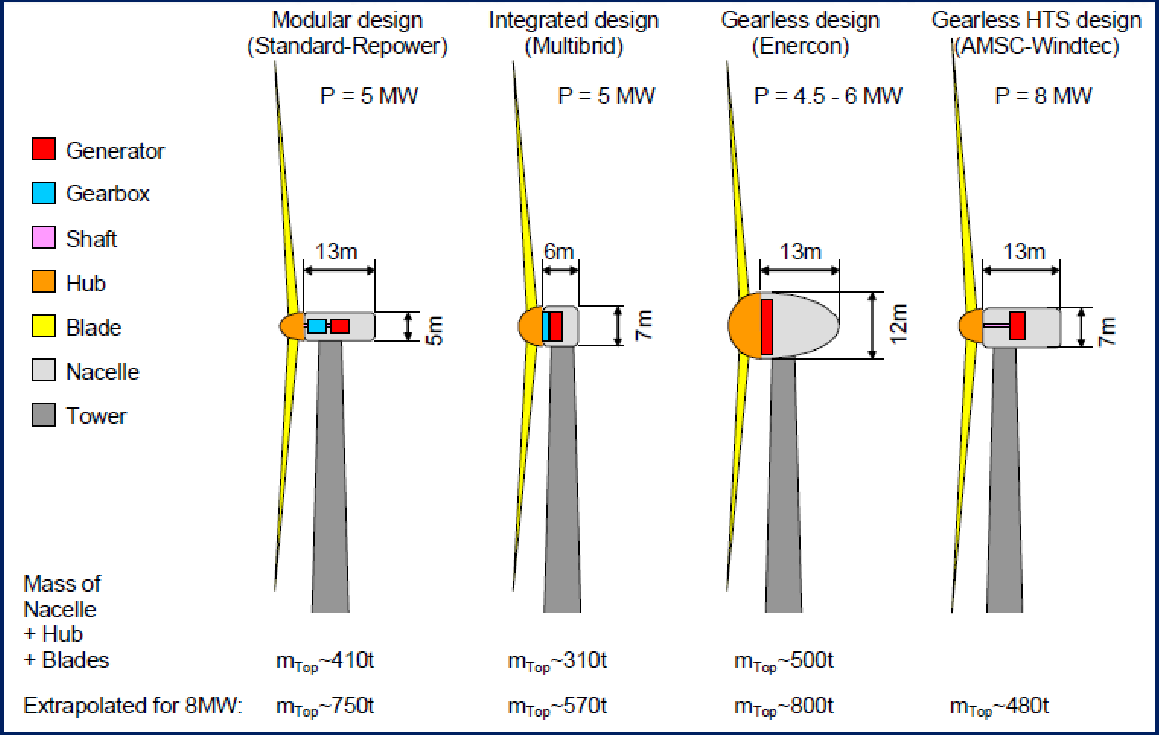
Direct drives saves weight and volume ~½

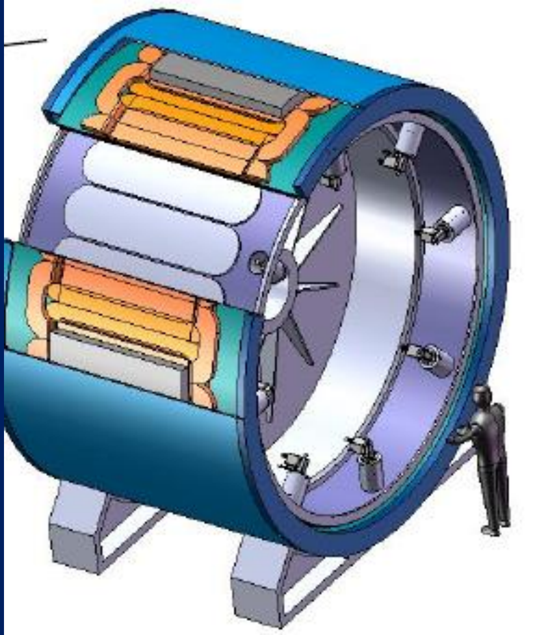
✓ Makes towers less heavy, cheaper

8 MW unit under development (AMSC)

Interest from European companies growing





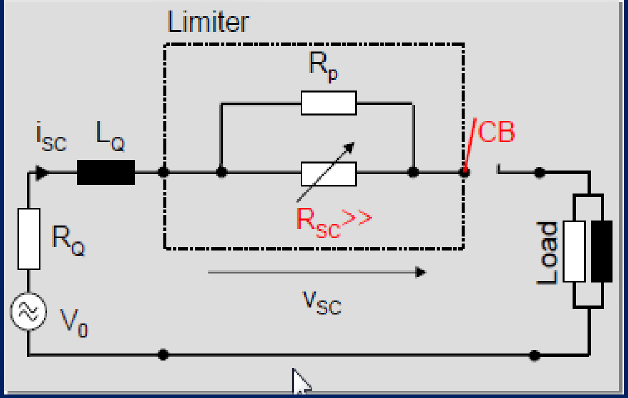


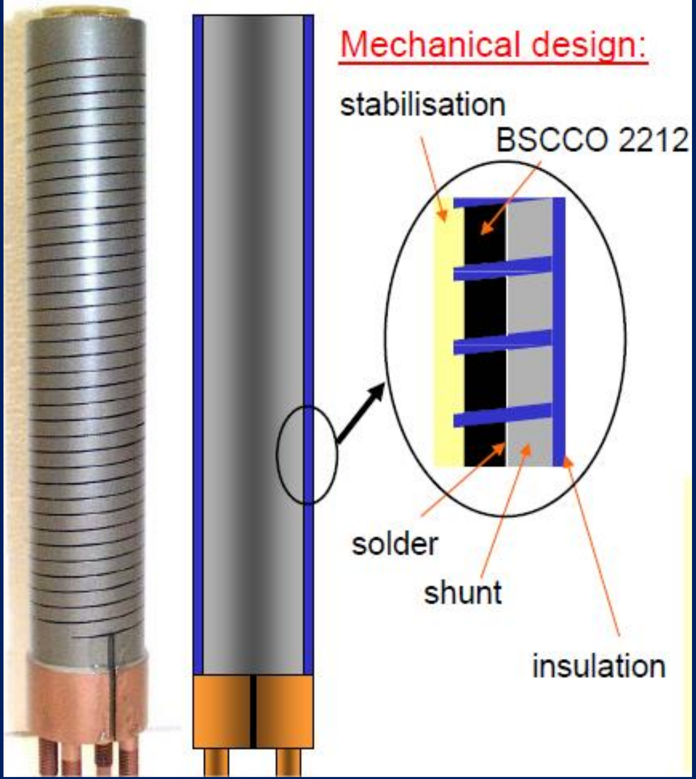
8 : Fault Current Limiter using Bi-2212 bulk

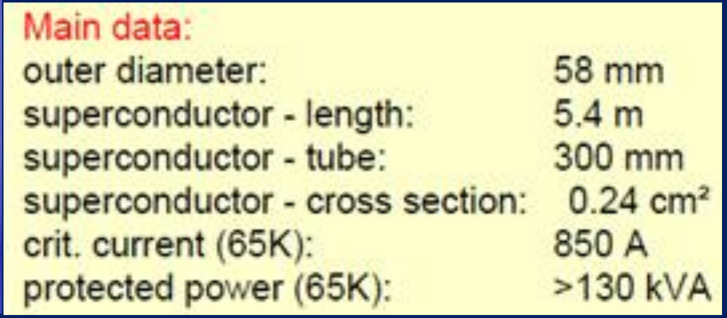
Resistive type

Switching bulk

Bi-2212 bifilar coils to resistive state



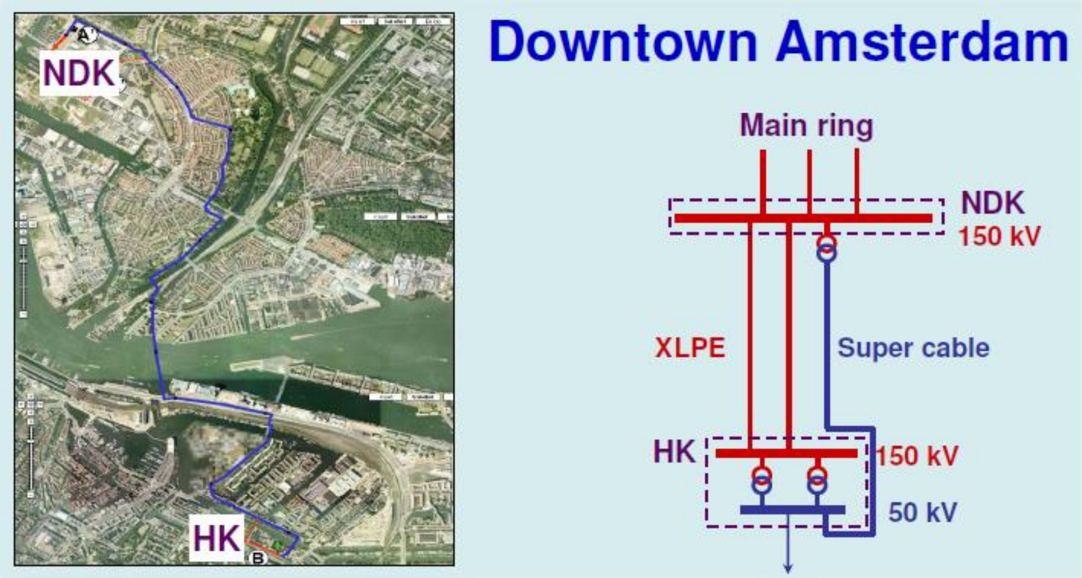


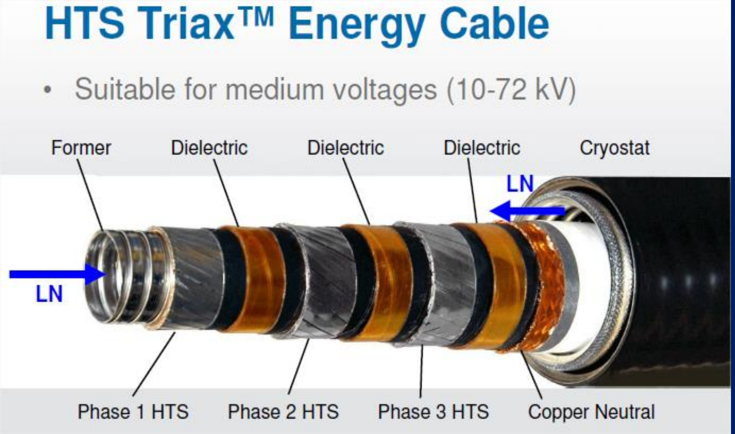


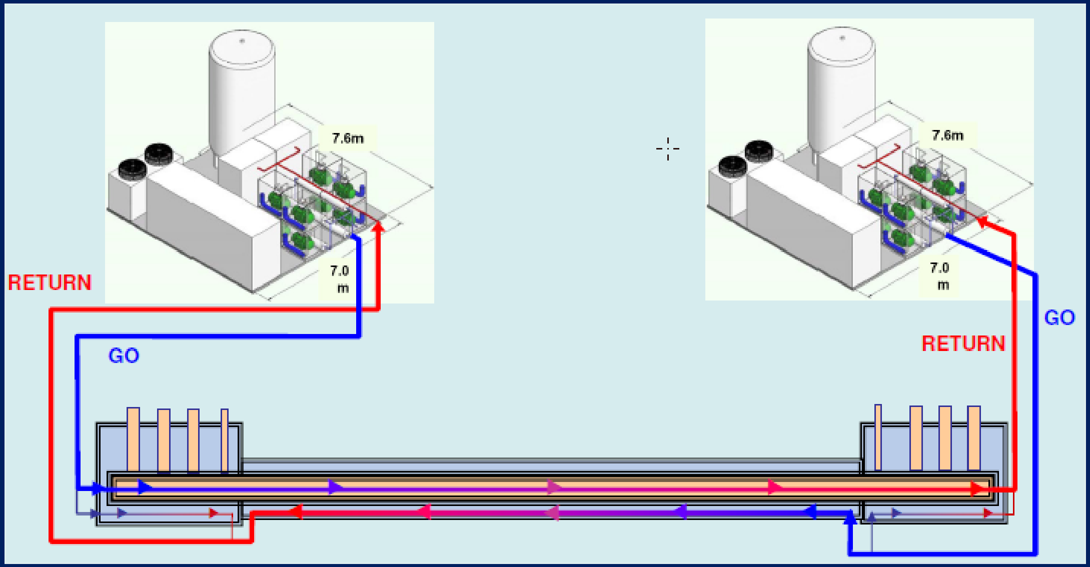
Main data:

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



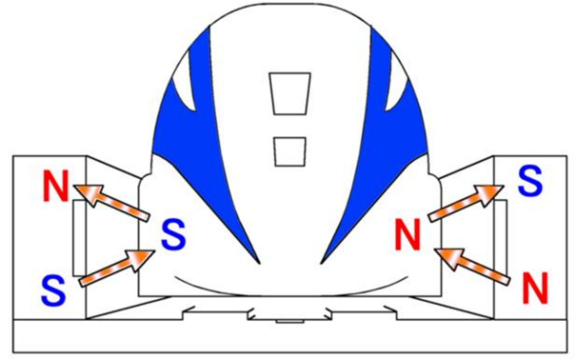




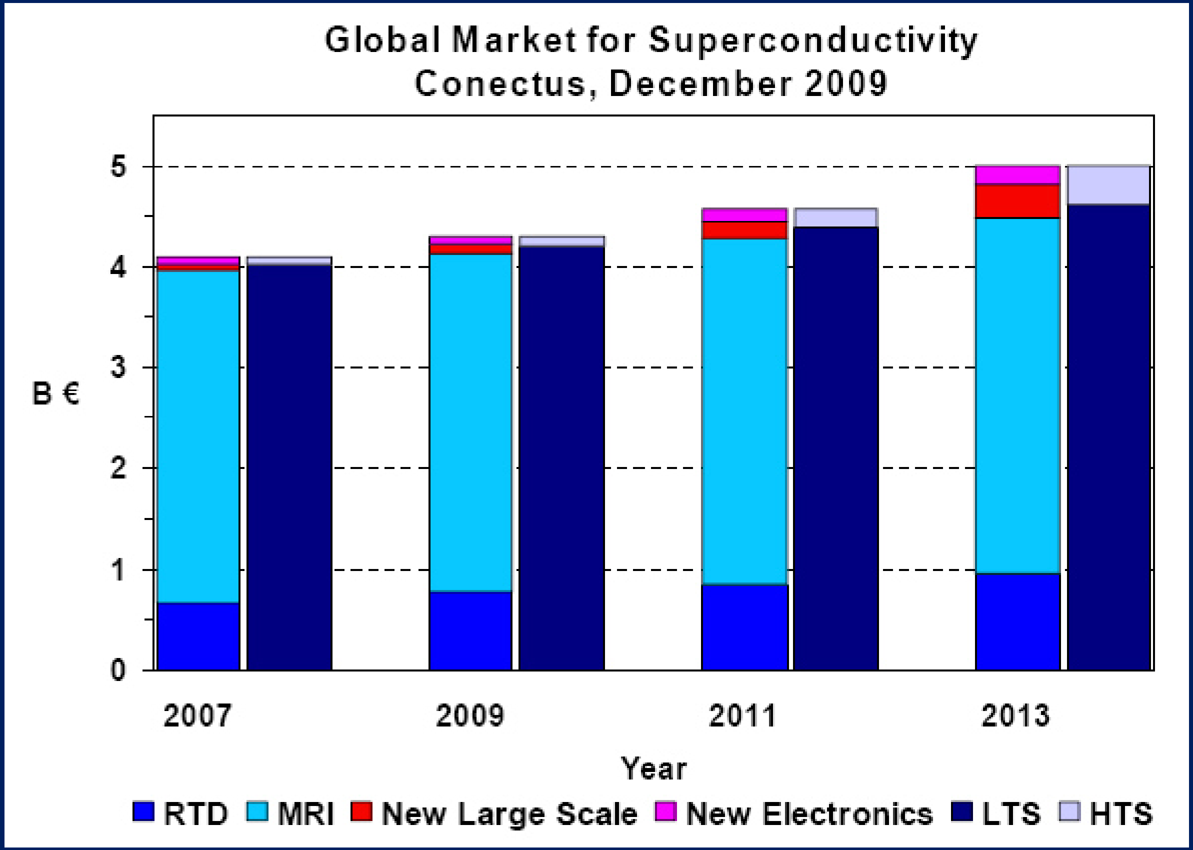
- Challenge in length never done before
- Requires adapted cooling system and perfect vacuum system
- Would be nice to see this happening, a real breakthrough

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

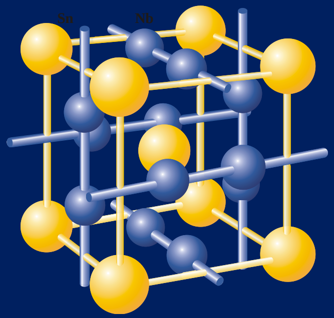


- ~ 5 B€/yr business, growing
- today dominated by MRI and Research Magnets, including NMR and accelerator magnets, >90 %

  and workhorse superconductors NbTi and Nb_3Sn >90 %

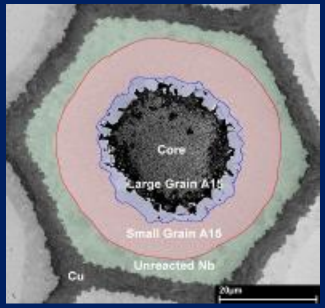
From materials to magnets

Lattice



50 nm

Filament



20 μm

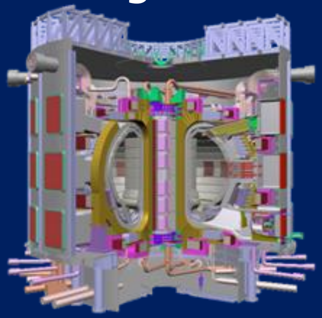
Wire

1 mm

Cable

50 mm

Magnet



35 meter

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

---> 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……….