Superconducting Materials for High Field Applications

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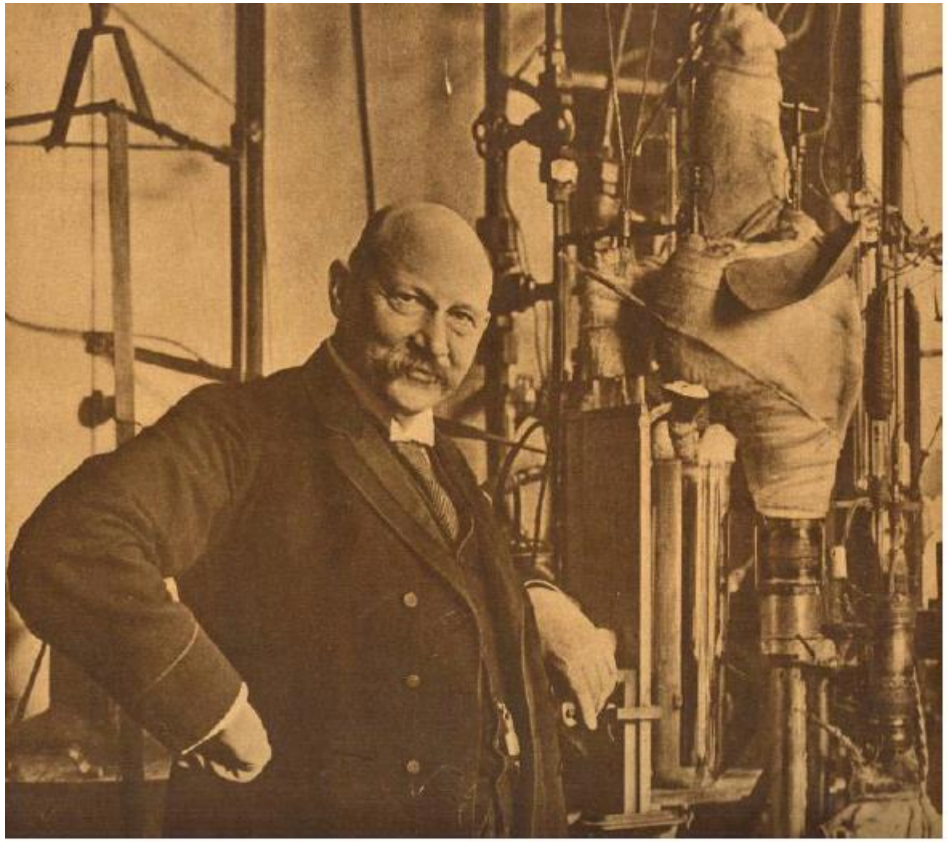
Outline

- **Introduction**
  - History of high-field
  - High field for accelerator technology
- **Superconductors**
  - Requirements for high-field applications
  - Low Temperature Superconductors: Nb-Ti and Nb_3Sn
  - High Temperature Superconductors: REBCO, Bi-2212 and Bi-2223
  - Superconducting cables: LTS and HTS
- **Future challenges**
  - Conductor development for future accelerators
- **Conclusions**

Liquefaction of helium gas



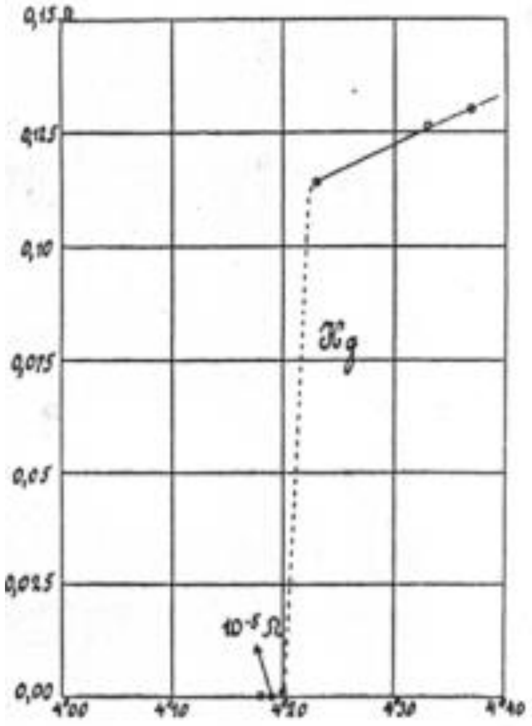
1908 Leiden physics laboratory, The Netherlands

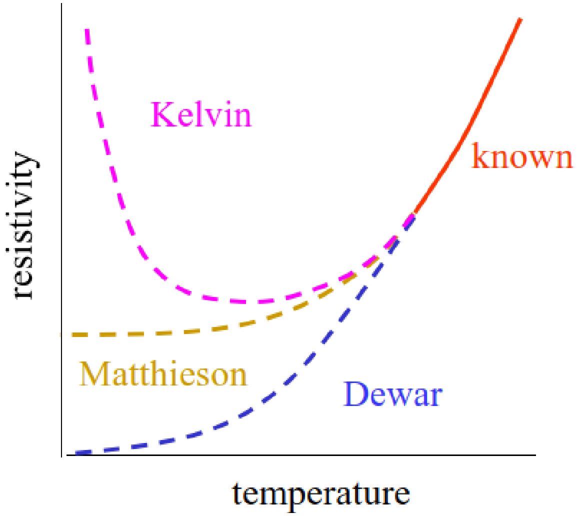
K. Onnes reached 4.2 K - and lowered temperature down to 1.8 K

Liquefaction of helium enabled discovery of **superconductivity in mercury in 1911**

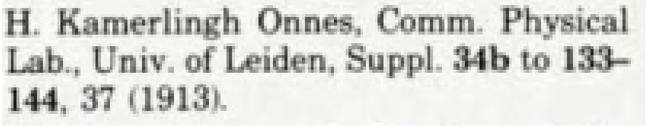
Kamerlingh Onnes: **Nobel prize in Physics in 1913** *“for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium”*

Resistence vs Temperature





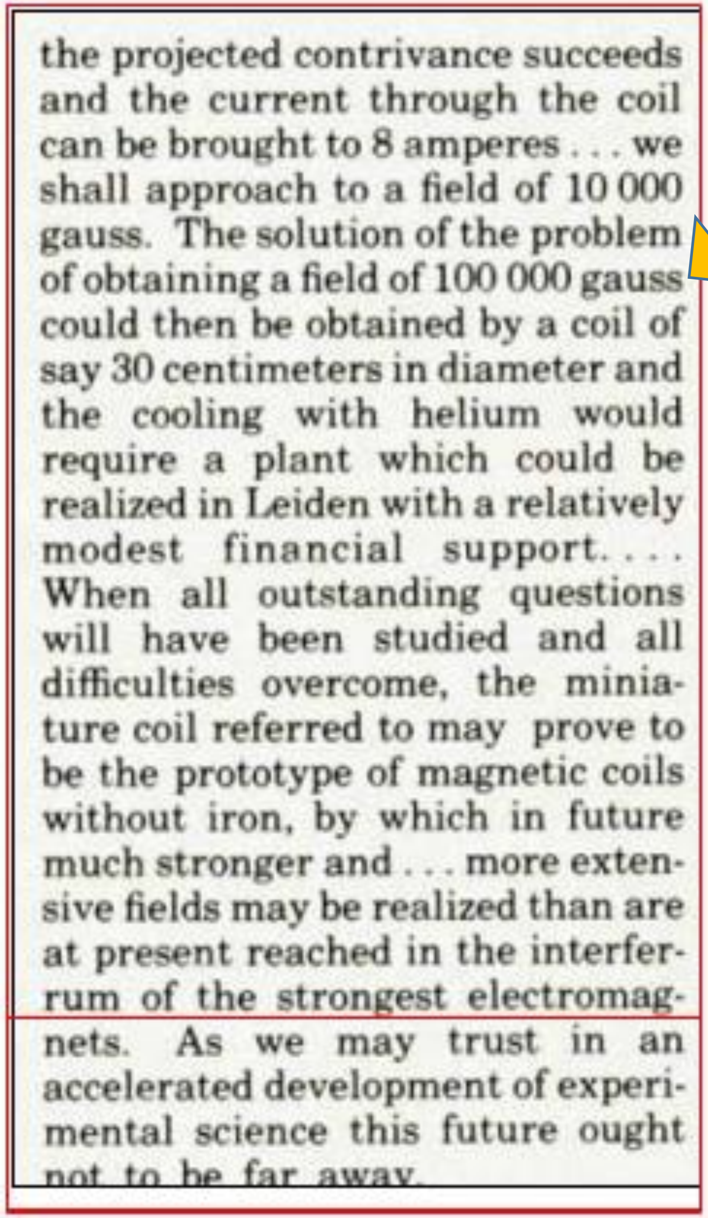
Onnes: thoughts on 10 T magnet (Chicago, 1913 !)

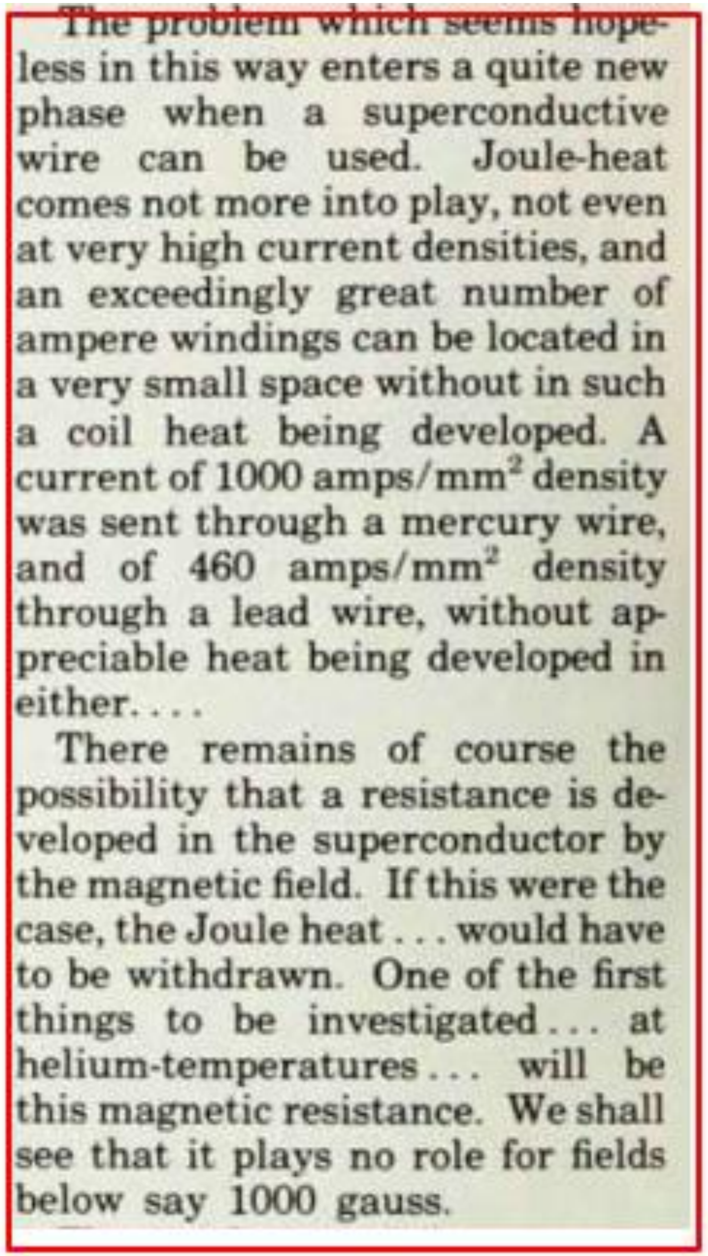

H. Kamerlingh Onnes, Comm. Physical Lab., Univ. of Leiden, Suppl. 34b to 133–144, 37 (1913).

First superconducting magnet 600 Gauss (0.06 T)

But: resistance developed at 0.8 A

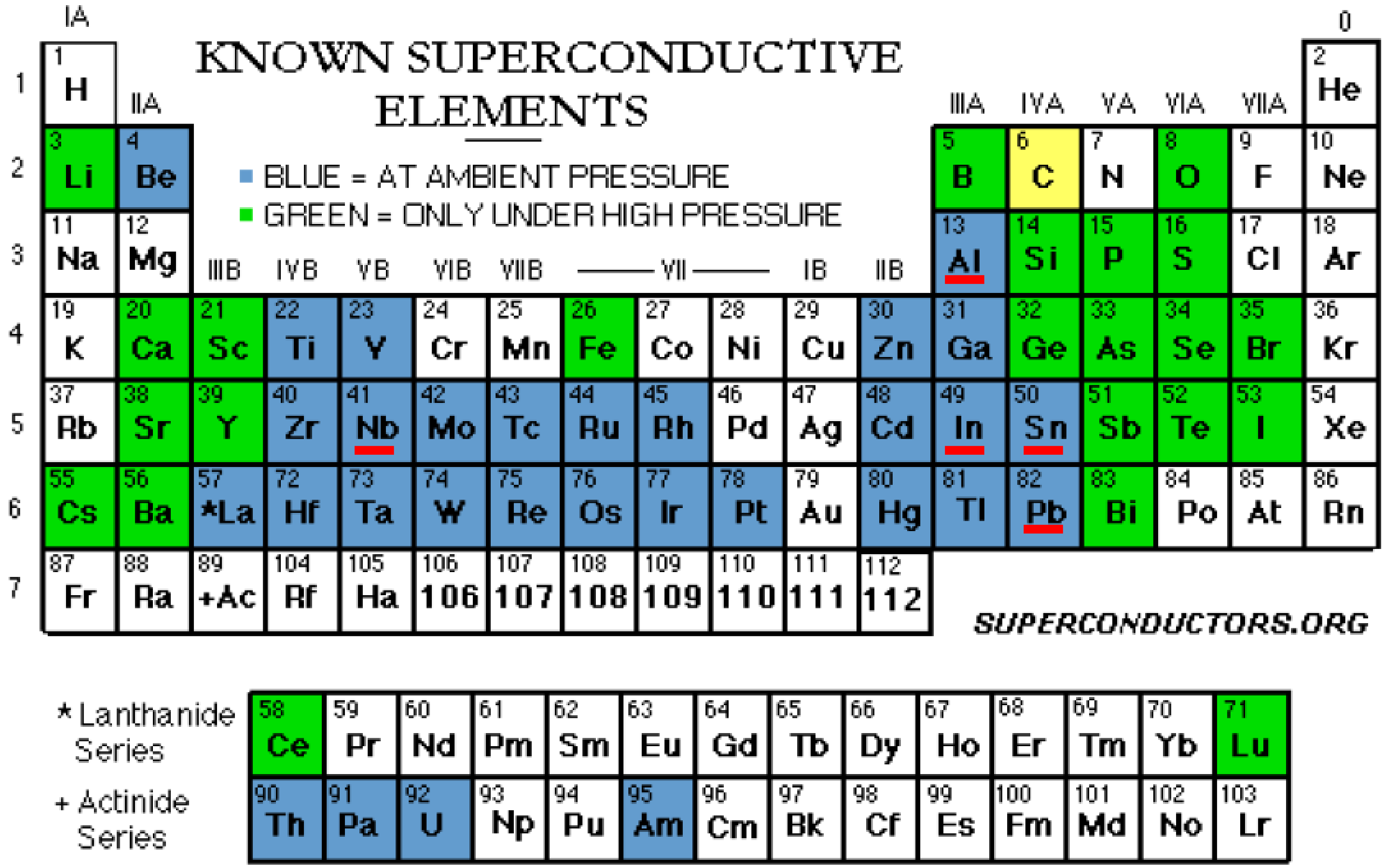
More than 40 years were needed for experimental high-field magnets !


the projected contrivance succeeds and the current through the coil can be brought to 8 amperes . . . we shall approach to a field of 10 000 gauss. The solution of the problem of obtaining a field of 100 000 gauss could then be obtained by a coil of say 30 centimeters in diameter and the cooling with helium would require a plant which could be realized in Leiden with a relatively modest financial support. . . . When all outstanding questions will have been studied and all difficulties overcome, the miniature coil referred to may prove to be the prototype of magnetic coils without iron, by which in future much stronger and . . . more extensive fields may be realized than are at present reached in the interferrum of the strongest electromagnets. As we may trust in an accelerated development of experimental science this future ought not to be far away.


The problem which seems hopeless in this way enters a quite new phase when a superconductive wire can be used. Joule-heat comes not more into play, not even at very high current densities, and an exceedingly great number of ampere windings can be located in a very small space without in such a coil heat being developed. A current of 1000 amps/mm^2 density was sent through a mercury wire, and of 460 amps/mm^2 density through a lead wire, without appreciable heat being developed in either. . . .

There remains of course the possibility that a resistance is developed in the superconductor by the magnetic field. If this were the case, the Joule heat . . . would have to be withdrawn. One of the first things to be investigated . . . at helium-temperatures . . . will be this magnetic resistance. We shall see that it plays no role for fields below say 1000 gauss.

Superconducting elements



KNOWN SUPERCONDUCTIVE ELEMENTS

🟦 BLUE = AT AMBIENT PRESSURE
🟩 GREEN = ONLY UNDER HIGH PRESSURE

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li 🟩	4 Be 🟦											5 B 🟩	6 C 🟨	7 N	8 O 🟩	9 F	10 Ne
3	11 Na	12 Mg											13 Al 🟦	14 Si 🟩	15 P 🟩	16 S 🟩	17 Cl	18 Ar
4	19 K	20 Ca 🟩	21 Sc 🟩	22 Ti 🟦	23 V 🟦	24 Cr	25 Mn	26 Fe 🟩	27 Co	28 Ni	29 Cu	30 Zn 🟦	31 Ga 🟦	32 Ge 🟩	33 As 🟩	34 Se 🟩	35 Br 🟩	36 Kr
5	37 Rb	38 Sr 🟩	39 Y 🟩	40 Zr 🟦	41 Nb 🟦	42 Mo 🟦	43 Tc 🟦	44 Ru 🟦	45 Rh 🟦	46 Pd	47 Ag	48 Cd 🟦	49 In 🟦	50 Sn 🟦	51 Sb 🟩	52 Te 🟩	53 I 🟩	54 Xe
6	55 Cs 🟩	56 Ba 🟩	57 *La 🟦	72 Hf 🟦	73 Ta 🟦	74 W 🟦	75 Re 🟦	76 Os 🟦	77 Ir 🟦	78 Pt 🟦	79 Au	80 Hg 🟦	81 Tl 🟦	82 Pb 🟦	83 Bi 🟩	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

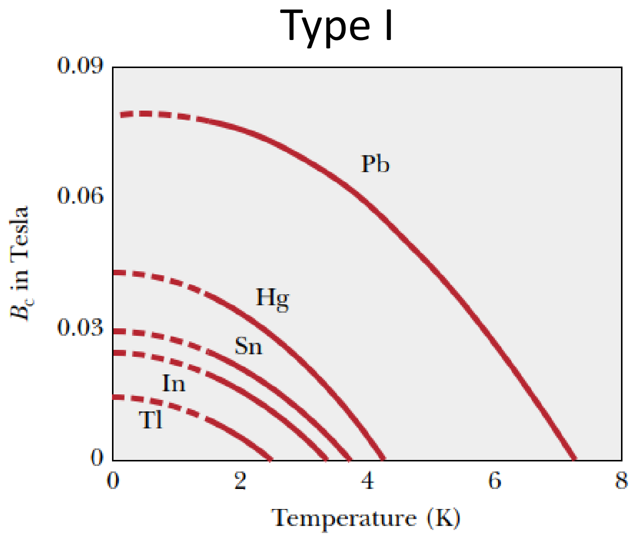
SUPERCONDUCTORS.ORG

* Lanthanide Series	58 Ce 🟩	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu 🟩
+ Actinide Series	90 Th 🟦	91 Pa 🟦	92 U 🟦	93 Np	94 Pu	95 Am 🟦	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Type I and Type II Superconductors

- **Type I** (most of pure metals) superconductors lose their superconductivity at low magnetic fields lower than 0.1 T)

- **Type II** superconductors (metallic compounds and alloys) identified in **1936**



Type II superconductors have wide applications in science and technology

History of Superconductivity

- 1908 Onnes liquefies He
- **1911** Onnes observe superconductivity in Hg (Type I) – Nobel prize 1913

  Superconducting era starts

- 1914 Persistent current experiments (Onnes)

25 years

- 1933 Meissner-Ochsenfeld effect observed
- **1936 Type II superconductors**
- 1950 Ginsburg - Landau theory – **Nobel price 2003**

46 years

- **1957** BCS Theory (Bardeen, Cooper, Schrieffer) – **Nobel Price 1972**

  Microscopic theory of Low Temperature Superconductivity

- 1962 Josephson effect is observed
- **1986** First observation superconductivity at **35 K** (Bednorz, Muller)

  High Temperature Superconducting era (HTS) starts

- 1987 first superconductor at **92 K** (above liquid Nitrogen at 77 K)

Theory

- **Bardeen-Cooper-Schrieffer (BCS) theory:** microscopic theory that describes **why materials are superconducting**. It is derived bottom-up from quantum mechanics

- **Ginzburg-Landau theory:** it describes **properties of superconductors in a magnetic field**. It is derived top-down from thermodynamics. It predicted vortex lattice and **Type II** superconductors. It enables simulation of vortex dynamics – with multi-vortex systems

Characteristic lengths

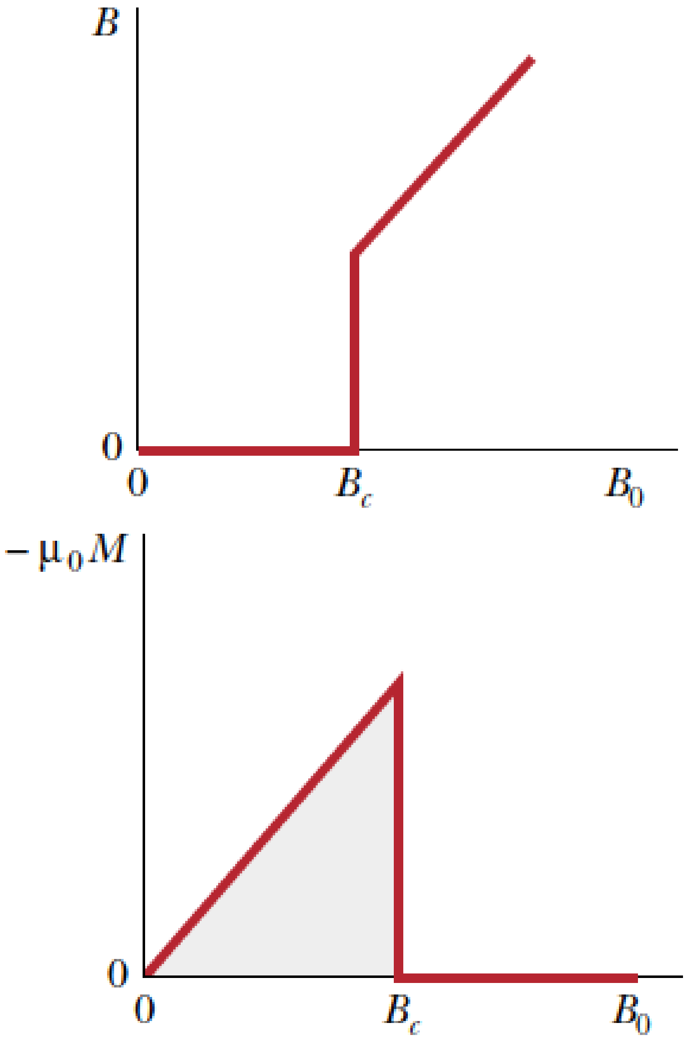
- Penetration depth λ(T)
  - Length over which an externally applied magnetic field is screened
- Ginzburg-Landau coherence length ξ(T)
  - Length over which superconducting order can be affected
- Ginzburg Landau parameter (almost independent on temperature):

$$k=\lambda/\xi$$

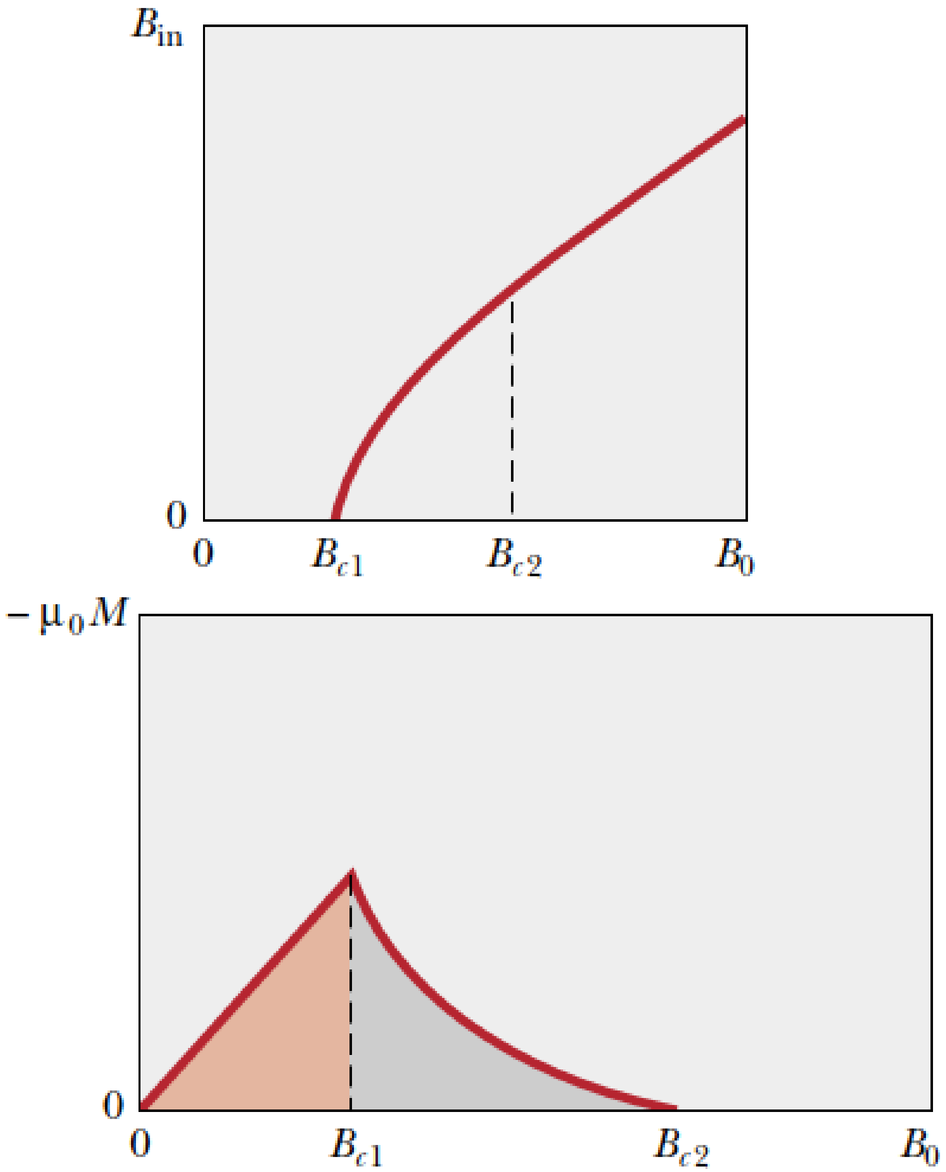
$$\boxed{\begin{array}{rl} \text{type I:} & \kappa < 1/\sqrt{2} \\ \text{type II:} & \kappa > 1/\sqrt{2} \end{array}}$$

Type I and Type II Superconductors

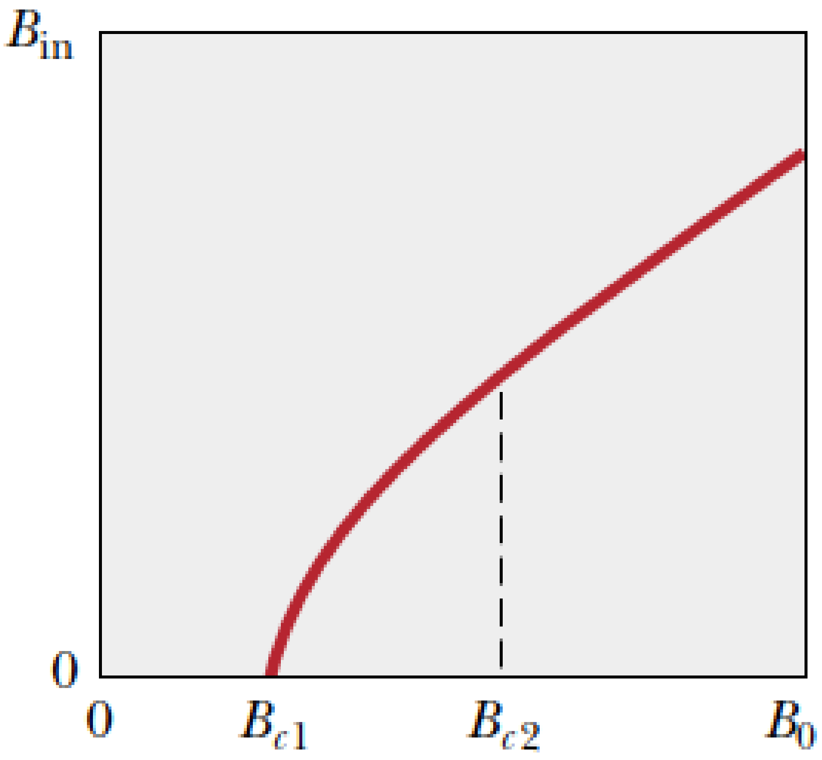
Type I



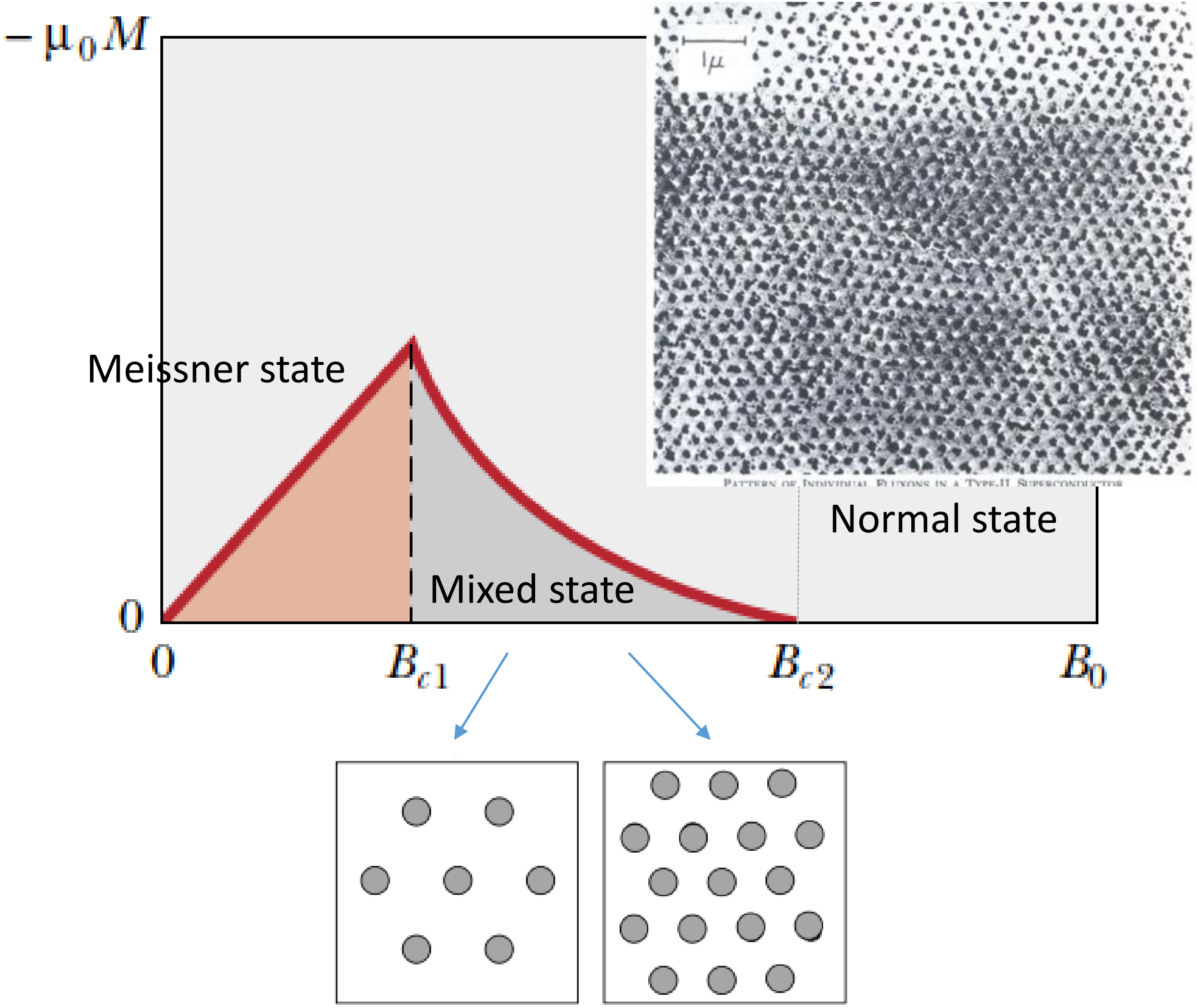
Type II

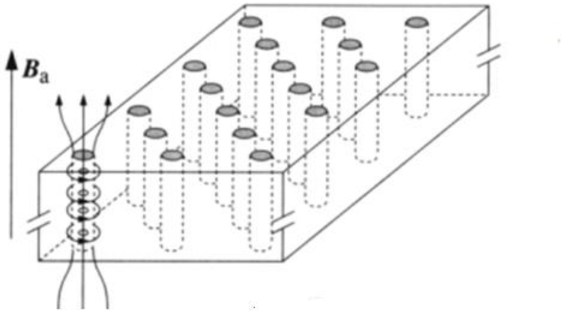


Type II Superconductors



Pattern of fluxoids in
Type II Superconductors





Type II Superconductors

- **Magnetic flux penetration** above **Bc1**

  Bc1 < 100 mT for Nb-Ti, N_3Sn, MgB_2 and HTS (REBCO, BSCCO 2223 and BSCCO 2212)

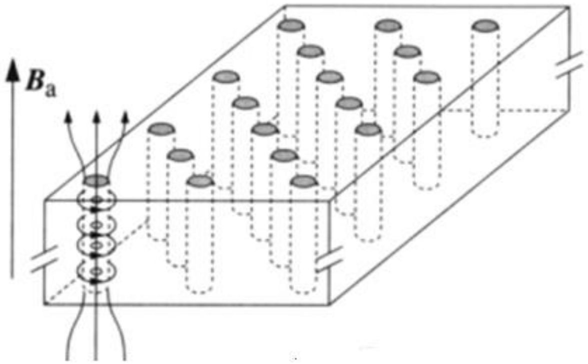
- Magnetic flux: array of **flux quantized line vortices** or fluxons

  Vortex: tube of radius of London penetration depth $\lambda(T)$
  Screening currents around a non-superconducting core of radius ξ (T)
  $\xi(T)$ = coherence length

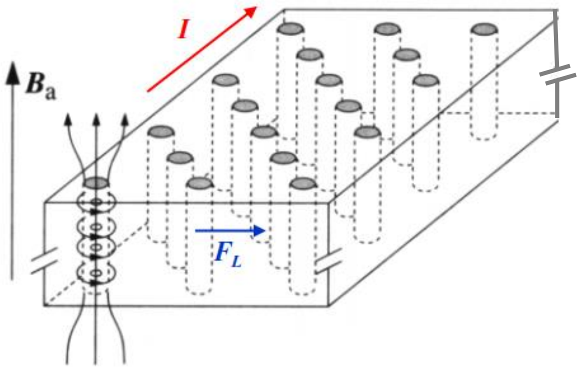
- Flux carried by **screening currents** for each vortex $\Phi_0 = 2\times10^{-15}$ Wb

$$\Phi = \frac{nh}{2e} = n\Phi_0 \qquad \Phi_0 = \frac{h}{2e} = 2.0679 \times 10^{-15}\ \mathrm{T \cdot m^2}$$

- Normal core overlap at **Bc2(T)** = $\Phi_0/2\,\pi\mu_0\xi(T)^2$



Type II Superconductors



- When a superconductor carries a current **I**:

  F_L = I ×B

- To avoid vortex motion, **pinning of vortices** at microstructural defects

- Process development is oriented to **optimize "flux pinning"**.

  Pinning centres must match with the fluxons spacing. In a triangular lattice:

$$d = \left\{ \frac{2}{\sqrt{3}} \frac{\phi_o}{B} \right\}^{1/2}$$

~ 20 nm at 6 T

- Maximum pinning strength is at absolute zero

Need to pin flux lines to avoid them moving under the Lorenz force (F_L)

Technical Superconductors

- **Low Temperature Superconductors**
  - Nb-Ti, Nb_3Sn
- **High Temperature Superconductors**
  - REBCO, BSCCO 2223, BSCCO 2212

High field applications
Industrially available

- **Medium Temperature Superconductors**
  - MgB_2
  - Iron based materials

Today for medium/low fields (< 5 T)

They have potential for high fields – but still a R&D material

Superconducting materials

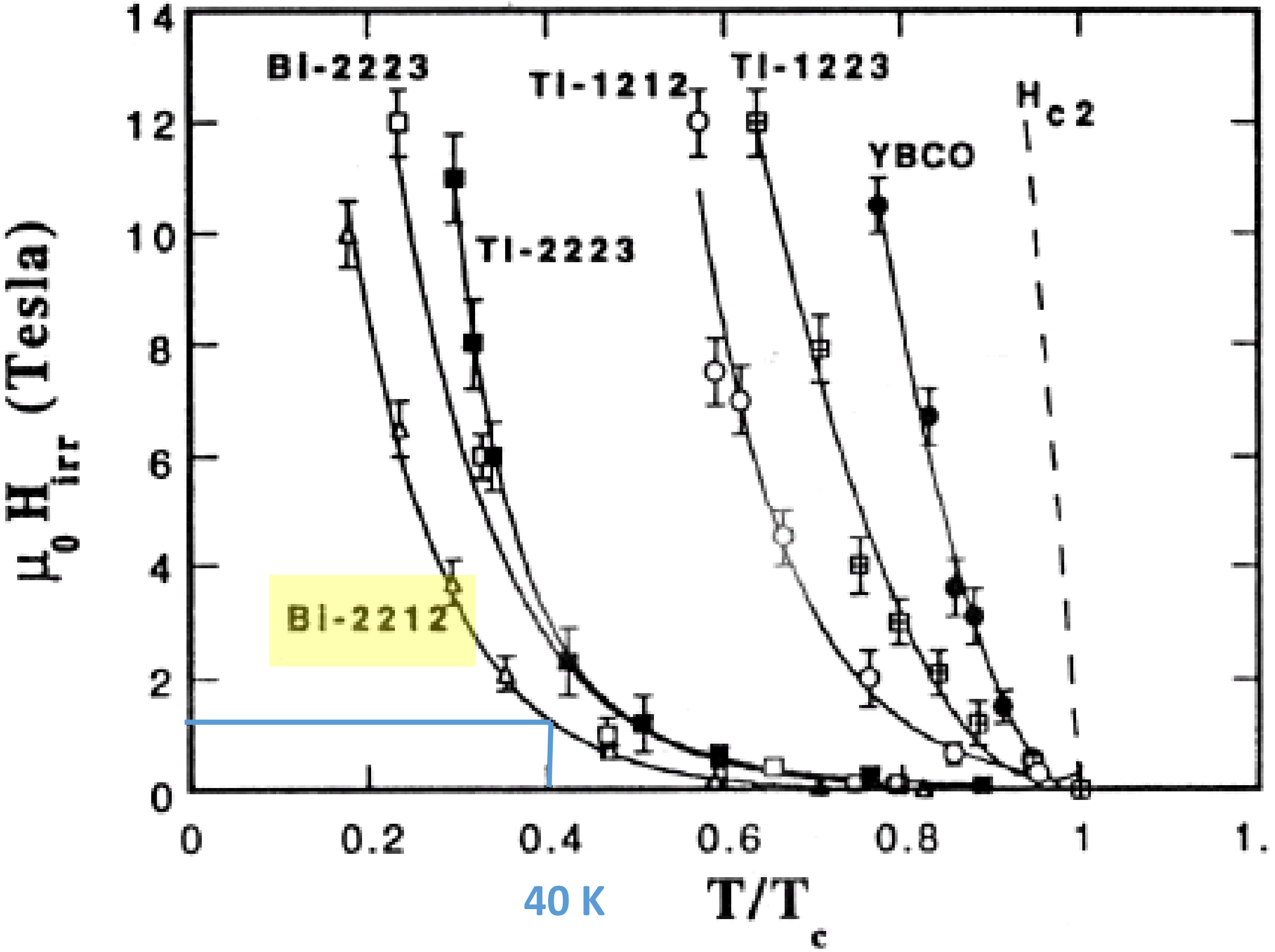
		Tc(0) [K]	Bc2(0 K) [T]	ξ (nm)
LTS	**Nb-Ti**	9.5	14.4	~ 6
	Nb$_3$Sn	18.3	28-30	~ 4
HTS	**REBCO**	93	> 100	~ 2
	BSCCO 2212	95	> 100	~ 1
	BSCCO 2223	110	> 100	~ 1

Bc2(0 K) > 100 T

Bc2(0) = upper critical field at 0 K
ξ = coherence length

Irreversibility field of HTS

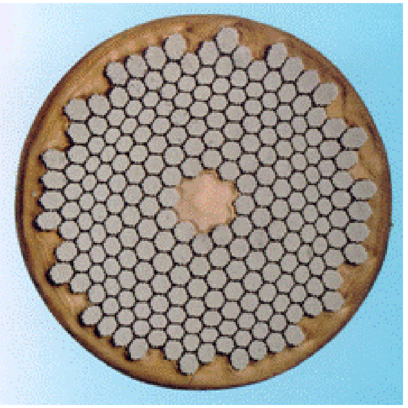
- **Bc_2(T)** much higher than for Nb-Ti and Nb_3Sn
- But, **thermal fluctuation** effects depress the irreversibility field (Birr(T)) at which Jc = 0 well below Bc2, except at low temperatures



High fields with HTS → Low (liquid helium) temperature

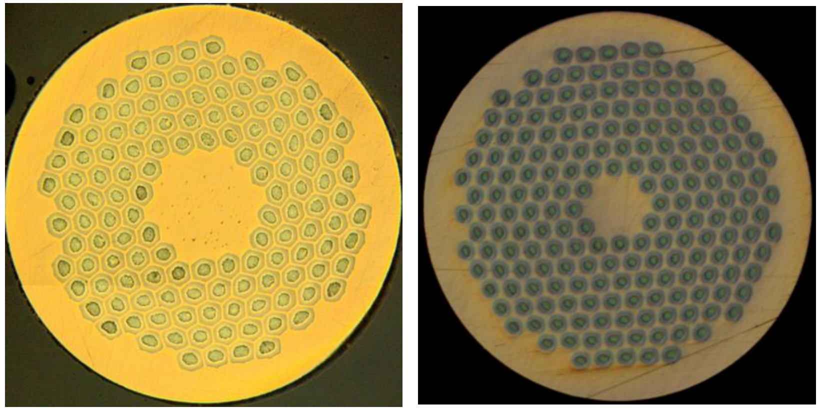
HTS vs LTS for high field applications

Nb-Ti



Up to ~ 10 T

Nb_3Sn



Up to ~ 15- 16 T

HTS at 4.2 K and for fields above 16 T

High-field applications of superconductors

- **Magnetic Resonance Imaging (MRI).** Non-invasive imaging technology. Clinical systems operate at 1.5 T- 3 T. For higher resolution: 7 T - 10 T, an up to 15 T
- **Nuclear Magnetic Imaging (NMR)**
- **Research magnets**
- **Fusion reactors**
- **Particle accelerators**

Pushed/push superconductors/magnets performance to exceed the frontier of high-energy particle physics

Superconductors for high-field applications

Needed:

- High **Hirr(Top)**
- High **Jc(Bop,Top)**. Typically Jc > 10^6 A/mm^2
  - Strong vortex pinning
  - Transparent grain boundaries
- Good **mechanical properties**
  - High critical tensile stress
  - High tensile, compressive and bending strains
- High **Je** (over total cross section)
- Acceptable **cost** enabling large scale applications

Superconductors for accelerator magnets (1/5)

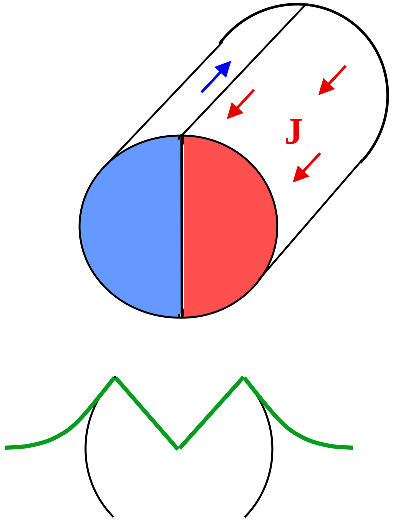
- **Very high and uniform current density** to produce a large field over a transverse aperture ($J_E \sim 400$ A/mm^2 at the operational field);
- **Multi-filamentary wire** with:
  - **Small filaments size** to:
    a) reduce magnetization and assure uniform field - mainly at injection;
    b) avoid flux jump (dynamic stability);
  - **Filaments twisted** to minimize coupling effects during ramping (eddy currents);
- **Appropriate (Cu/non Cu) ratio** - minimum amount of copper needed for stability and protection, controlled within a strict tolerance (typically 1.5-2 ± 0.05 for accelerator magnets);
- **High RRR** (low resistivity) of the copper matrix/stabilizer

Accelerator magnets have always pushed the limits of superconductors performance to beyond state-of-the-art

Superconductors for accelerator magnets (2/5)

- Small filaments size

Cylindrical filaments



Magnetization for fully penetrated filaments

$$M = \frac{2}{3\pi} J_c \, \Phi_f$$

Small Φf to reduce M

M=magnetic volume per unit volume

Jc(B,T) = critical current density

Φf = filament diameter

Beams are injected in a circular machine at **low energy** (0.45 TeV, i.e. 0.54 T for dipoles in LHC)

Persistent magnetization currents
inside the individual filaments of a wire generate field distortions

Superconductors for accelerator magnets (3/5)

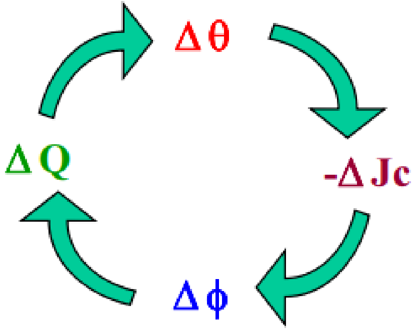
- Small filaments size

$$d \le \frac{2}{J_c}\left\{\frac{3\gamma\, C(\theta_c-\theta_o)}{\mu_o}\right\}^{\frac{1}{2}}$$

Maximum stable diameter of a filament in as metal matrix

γ = density
θc = critical temperature
C = specific heat

For Nb-Ti, d < 50 µm



Flux-jump: magnetic-thermal instability

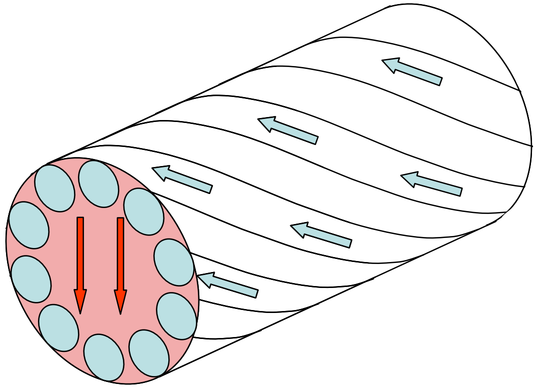
Instability of persistent currents

Flux-jump: usually not a problem for HTS

Small filaments to avoid flux jump

Superconductors for accelerator magnets (4/5)

- Filaments twisted



Coupling currents between filaments in a wire

$$\mathrm{M} = \frac{2\,\frac{dB}{dt}\,\tau}{\mu_0}$$

$$\tau = \frac{\mu_0}{2\,\rho_m}\left(\frac{L_t}{2\,\pi}\right)^2$$

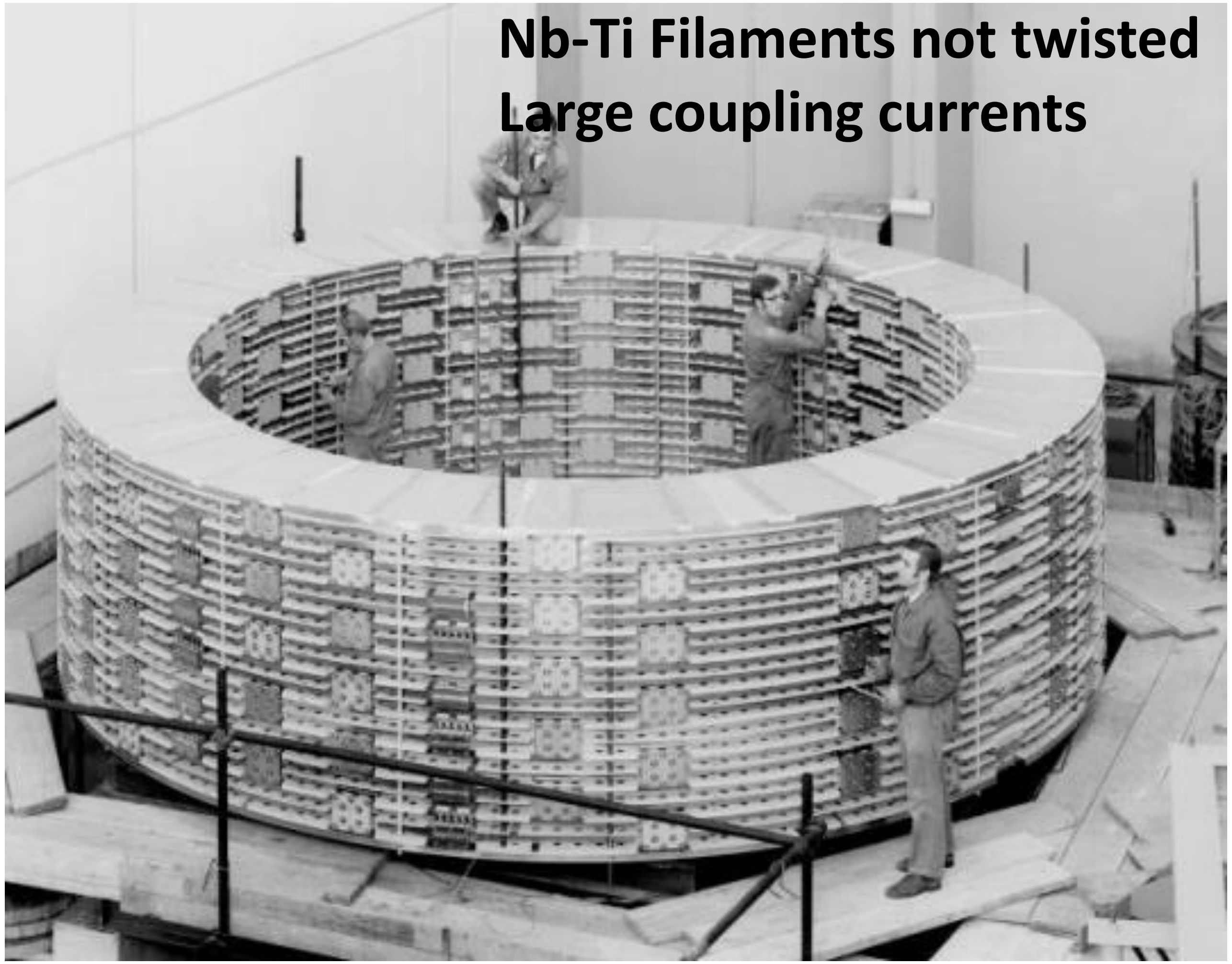
L_t = Twist pitch
ρ_m = transverse resistivity of the matrix

An un-twisted conductor is useless for magnets accelerator application

Superconductors for accelerator magnets (5/5)

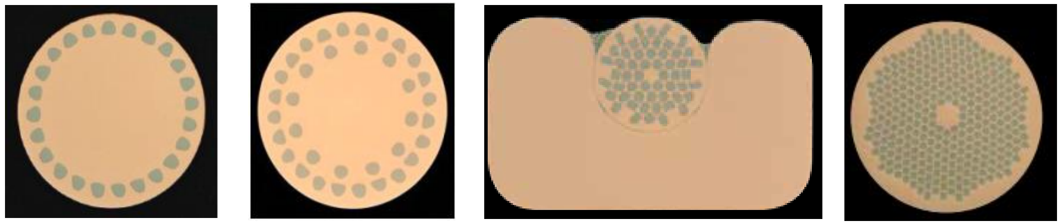
Big European Bubble Chamber (BEBC) at CERN - 1971

3.5 T solenoid
5.7 kA
800 MJ
Φbore = 4.72 m



Nb-Ti Filaments not twisted
Large coupling currents

Nb-Ti


Bruker's wires

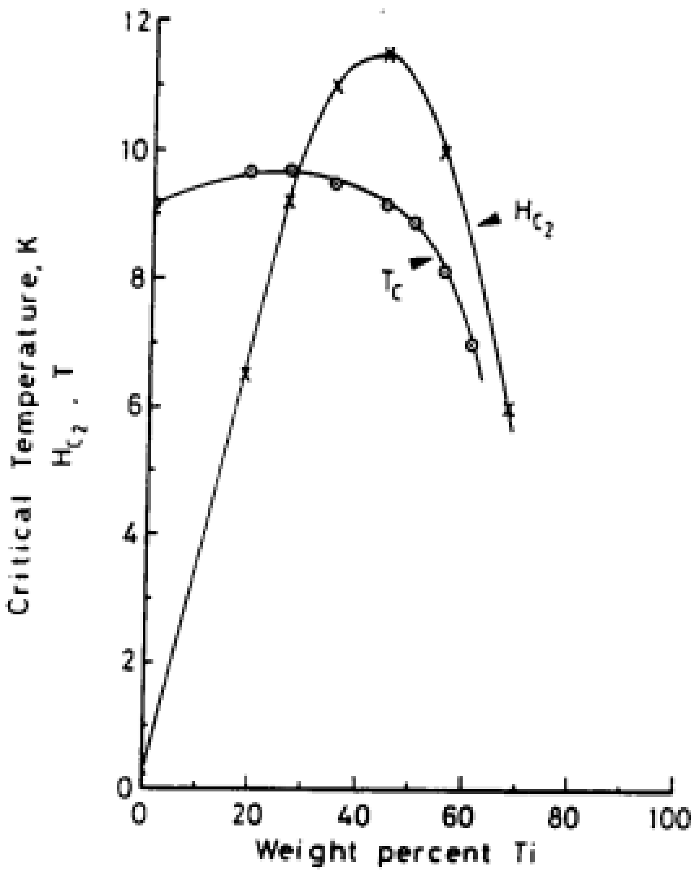

Luvata's wires

- Industrially available in a **large variety of architectures**
- **Fully optimized**, with processing and properties well understood
- Strong and dense engineered **pinning** thanks to **α-Ti precipates**
- The **only material to date** used in **accelerator magnets** and the material used in commercial **MRI magnets**
- Produced in **large quantity** (~ 600 tons/year, mainly for MRI) and long unit lengths at **low cost**. The **LHC** required about **1300 tons** of high-quality Nb-Ti (300 tons/year peak production)

The choice for magnetic fields ≤ 10 T

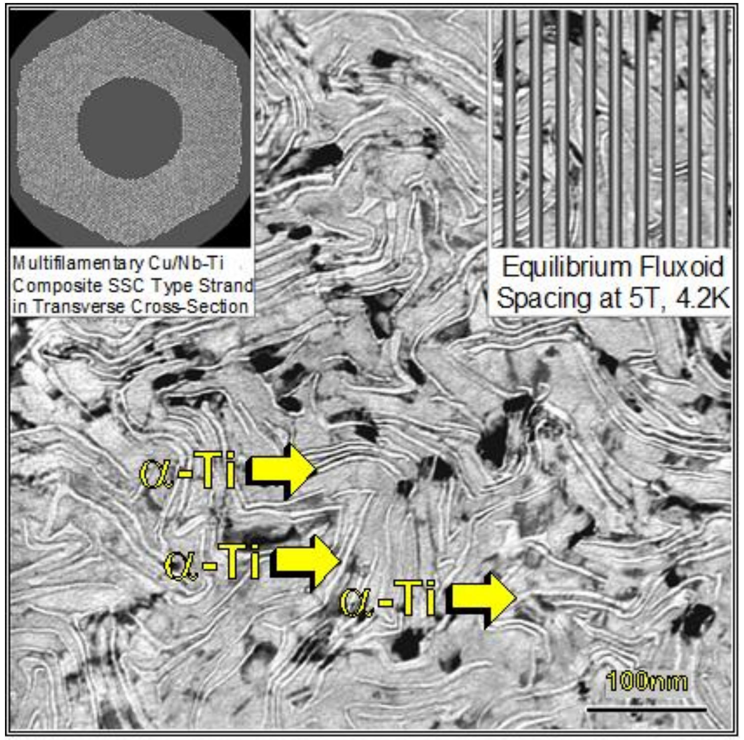
Nb-Ti

Nb-47wt%Ti



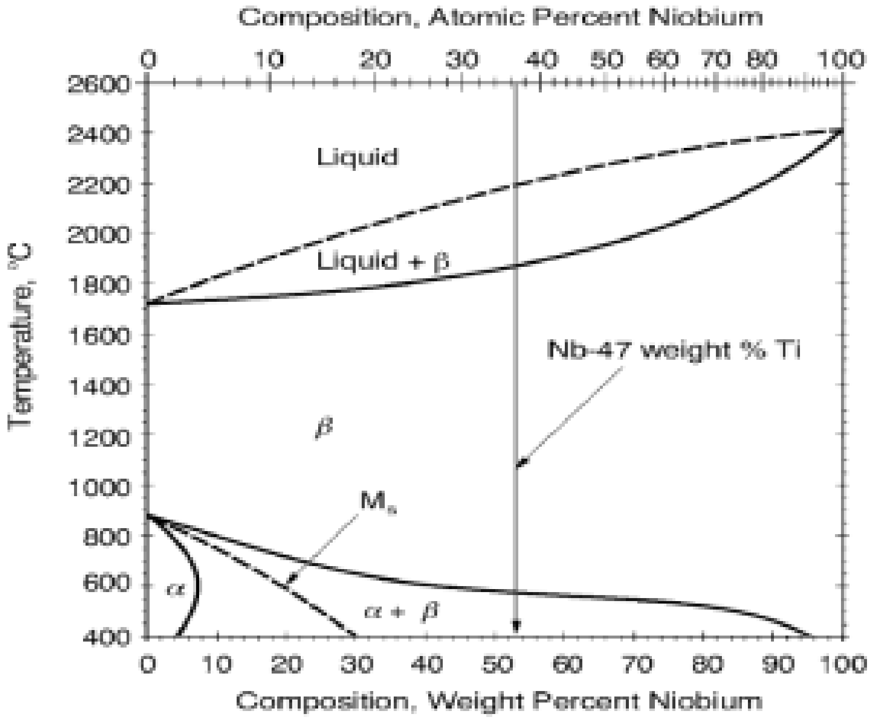
Optimum Bc2: Nb 46.5-50 wt% Ti

Nb-Ti: α-precipitates



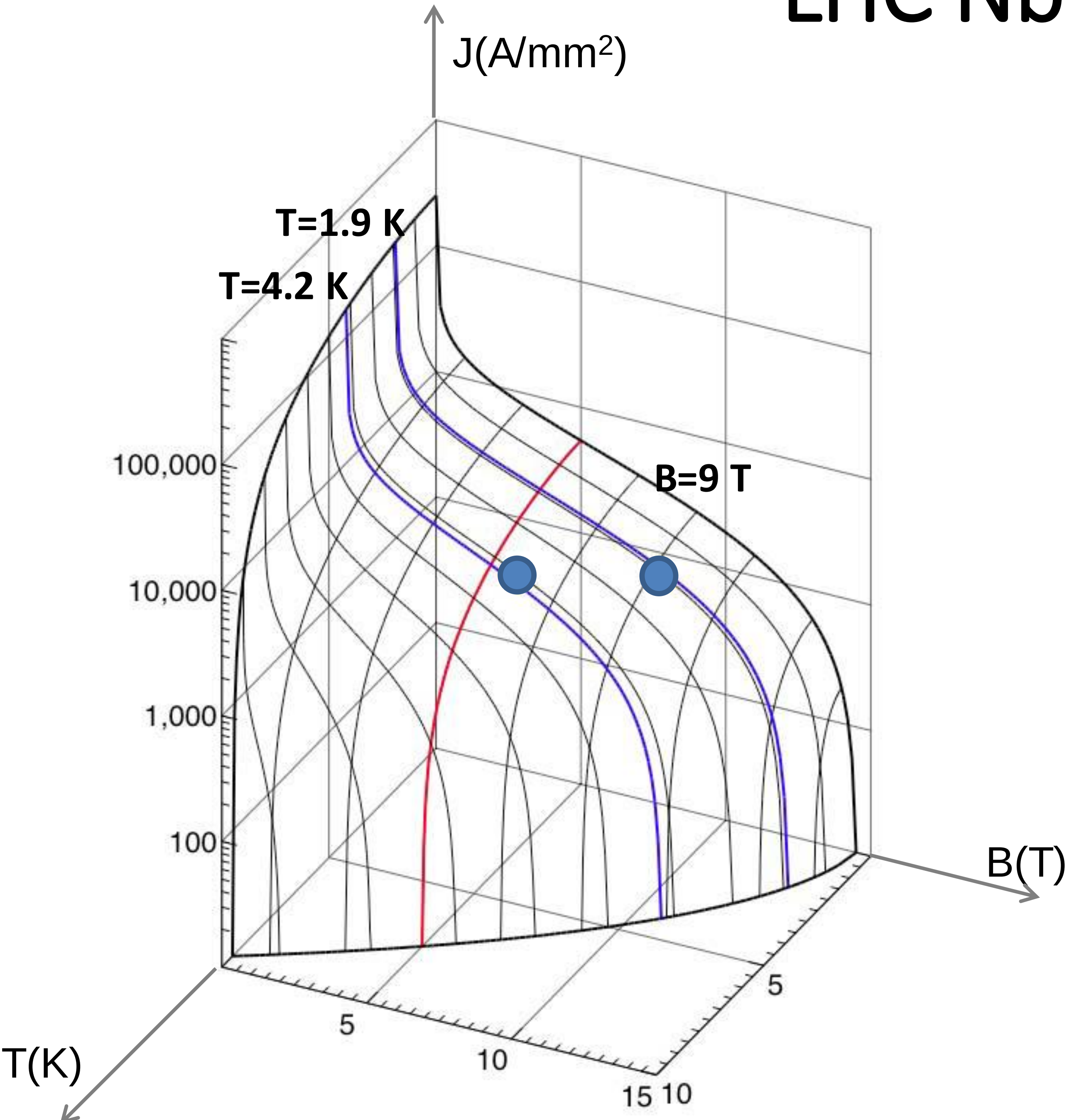
Meingast, Lee and DCL,
J. Appl. Phys. 66, 5971

Phase diagram



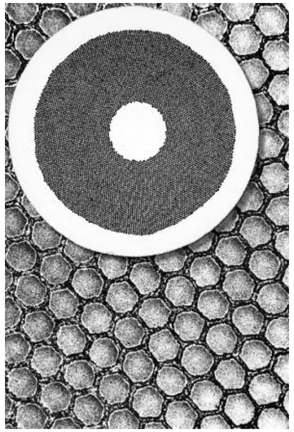
Ti rich phase precipitated as a result of heat treatments applied during manufacturing of the wire

LHC Nb-Ti wire



Jc(4.2 K, 6 T)~2300 A/mm^2

Jc(1.9 K, 9 T)~2300 A/mm^2



STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (μm)	7	6
Number of filaments	8800	6425
Jc (A/mm^2) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ_0M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5

240 000 km of Nb-Ti **wire**

5300 Nb-Ti/Cu composite

490 tons of **Nb-Ti** (47.0 ± 1.0 wt % Ti)

Nb-Ti is the choice for magnets

Unless we can’t….

Nb_3Sn

- **Bc2(2 K) ~ 30 T** (Bc2(2 K) of Nb-Ti ~ 14 T)

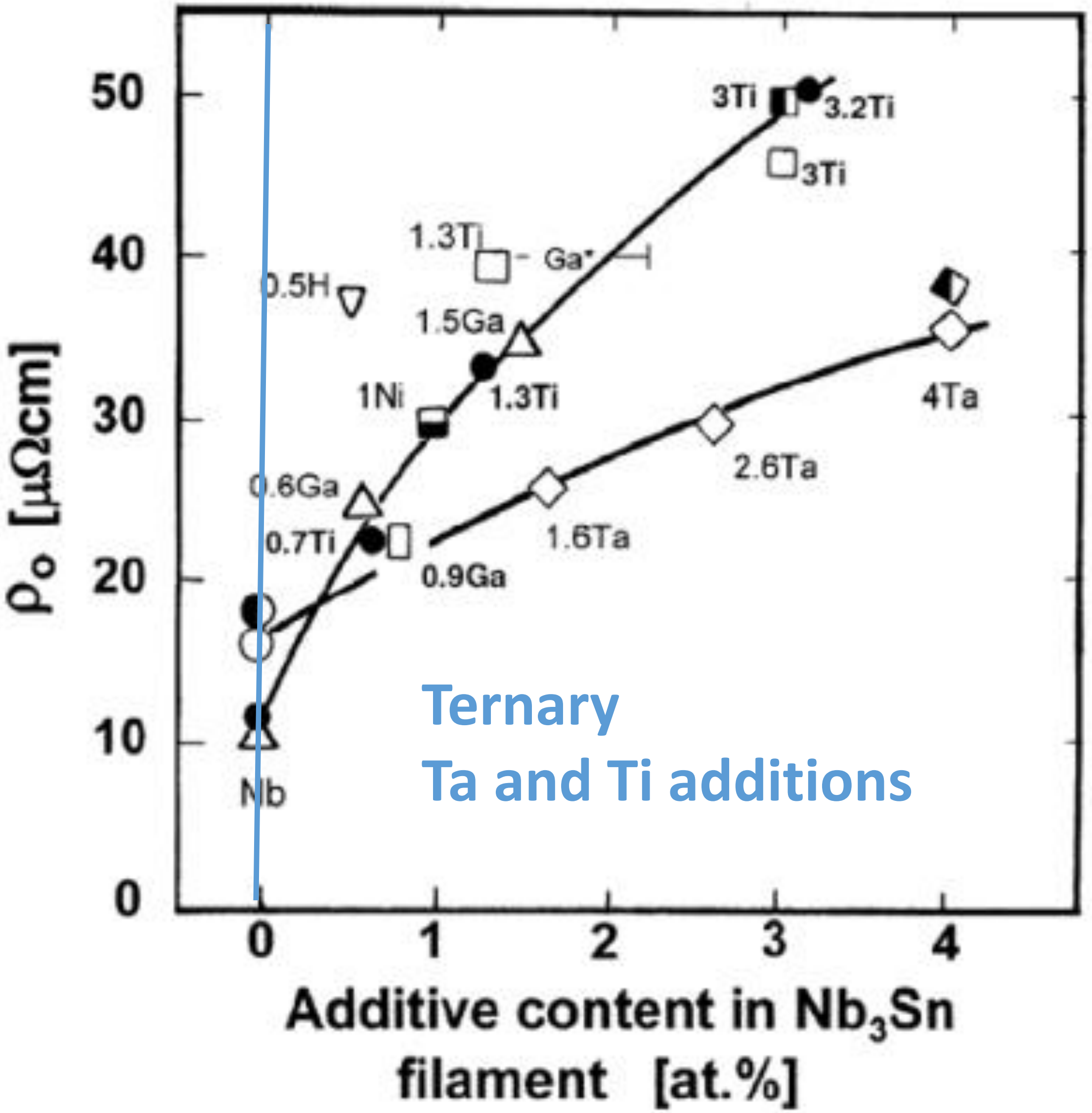
- **Brittle** intermetallic

- Ternary **$(NbTi)_3Sn$** or **$(NbTa)_3Sn$** compounds
  → Bc2 enhanced by increasing ρ_n without sacrificing Tc and workability (1-2 % at Ti and 2-4 at % Ta)

- **Multi-filamentary wires**, $\Phi \sim 1$ mm, filaments/sub-elements size ~ 60 μm

The choice for magnetic fields up to 15 T – 16 T

Nb_3Sn



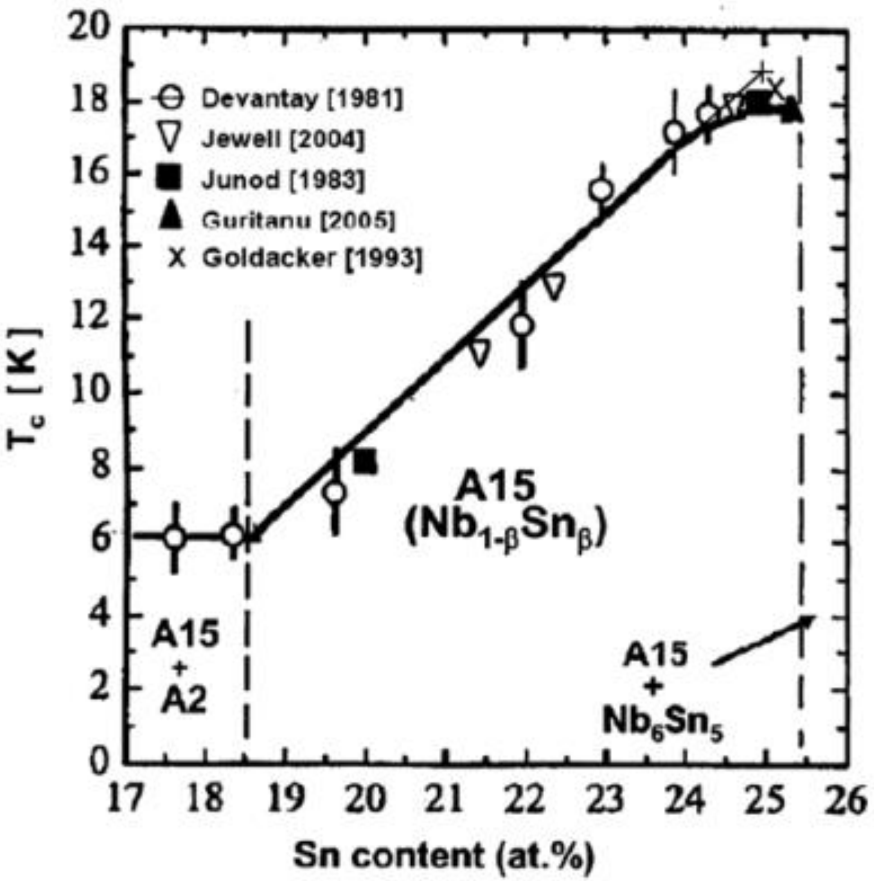
R. Flukiger et al., SuST 2008

Enhancement of ρ_0

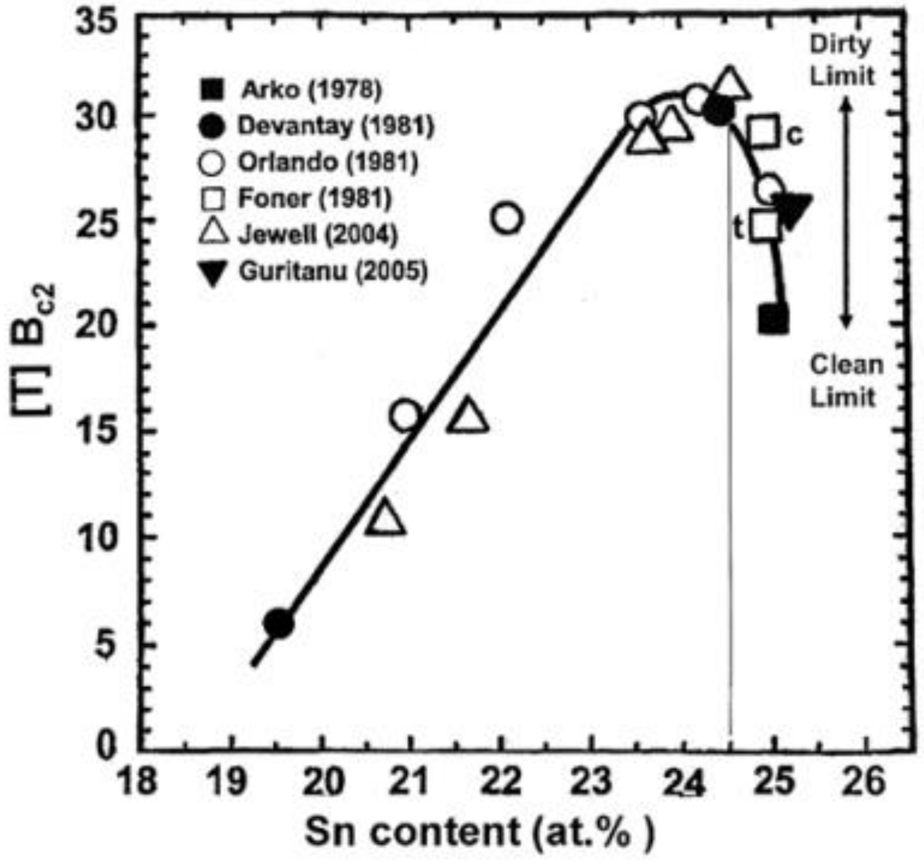
Enhancement of Bc2

$$\boxed{Bc2 \sim Tc\,\gamma\,\rho_0}$$

Nb_3Sn



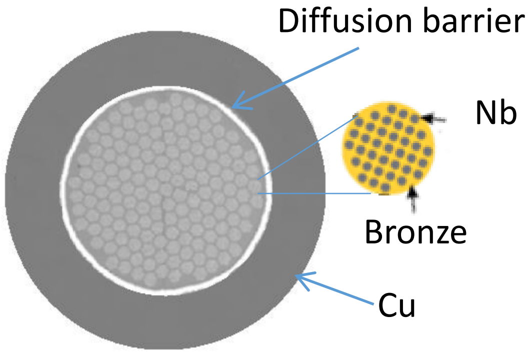
R. Flukiger et al., SuST 2008



Bc2 max at 24.5 at % Sn

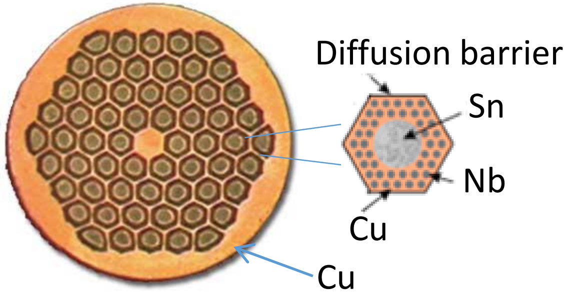
Nb_3Sn – Manufacturing Processes

Bronze Route



Small filaments ($\Phi < 5\ \mu m$)
Jc limited (~ 1-1.2 kA/mm^2 @ 12 T, 4.2 K) by the solubility of Sn in Cu (~15.5 wt %)

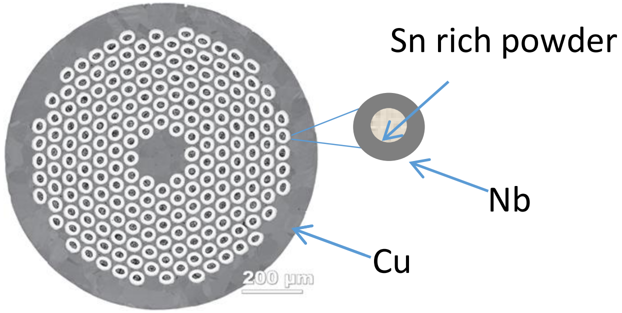
Internal Tin



RRP ®

High Jc Nb_3Sn wires for accelerator magnets

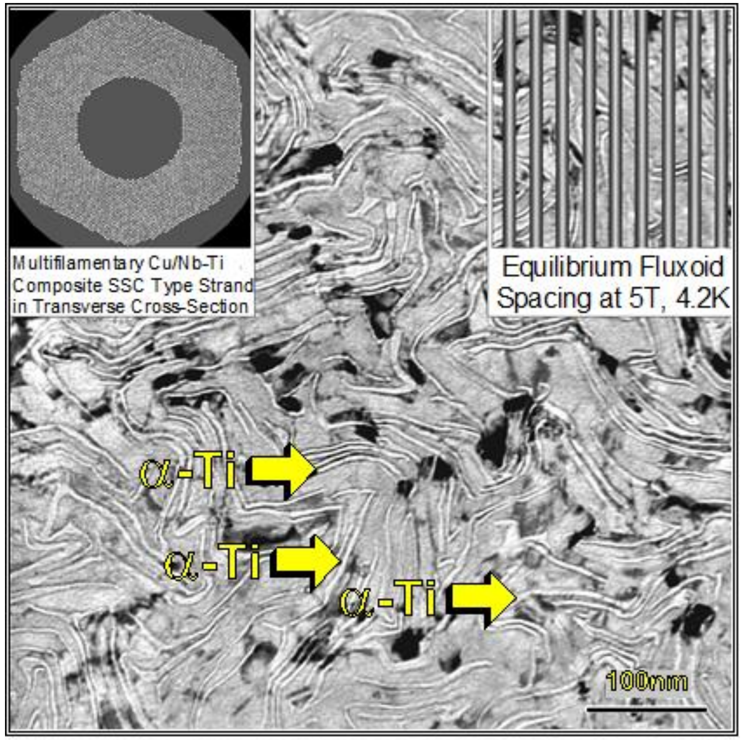
Powder In Tube



PIT

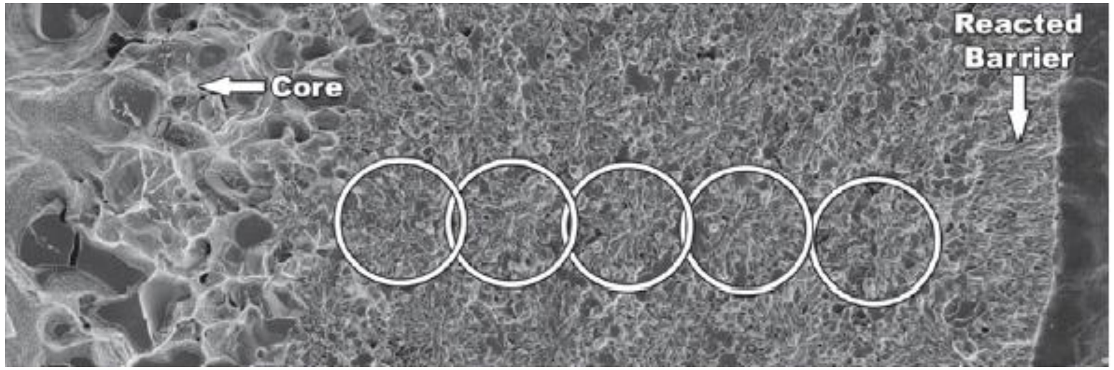
Nb_3Sn – Pinning mechanism

NbTi: α-precipitates



Meingast, Lee and DCL,
J. Appl. Phys. 66, 5971

Nb_3Sn: grain boundaries



C. Tarantini et al, Supercond . Sci. Technol. 27 (2014)

Dominant **pinning mechanism**:
grain boundaries (vortex pinning)

Finest grain size needed to maximise vortex pinning

Nb_3Sn – High Performance

- **Use all Nb and Sn** in the to make Nb_3Sn
  - Maximize the amount of A15
- Make **stoichiometric A15**
  - Avoid composition gradients
- Make **grains as small as possible**
  - Assure strong pinning

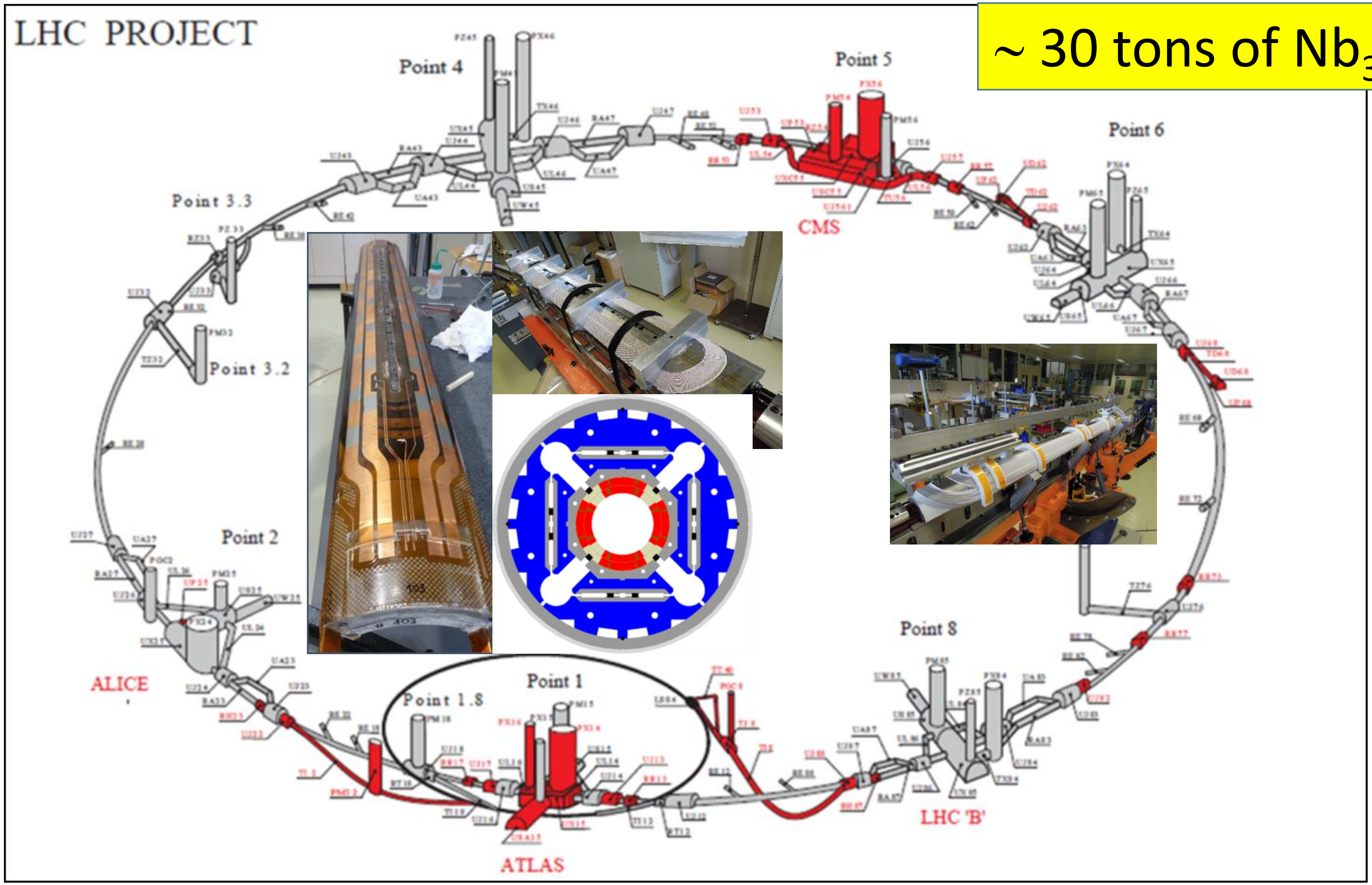
Nb_3Sn – Grain Size Refinement

- **Grain size** at optimized heat treatments ($\Phi \sim$**150 nm**) vs **vortex spacing** at operational fields (~ **12 nm** at 16 T) . Needed matching of spacing of pinning sites to vortex spacing
- **Grain refinement** possible by **lowering the reaction temperature**. **But** this is in conflict with the need of reaching stoichiometric Sn composition in the A15 phase → delicate interplay between A15 gain boundary density and compositional homogeneity

High-Luminosity LHC Project

Nb_3Sn for the first time in an operating accelerator

~ 30 tons of Nb_3Sn

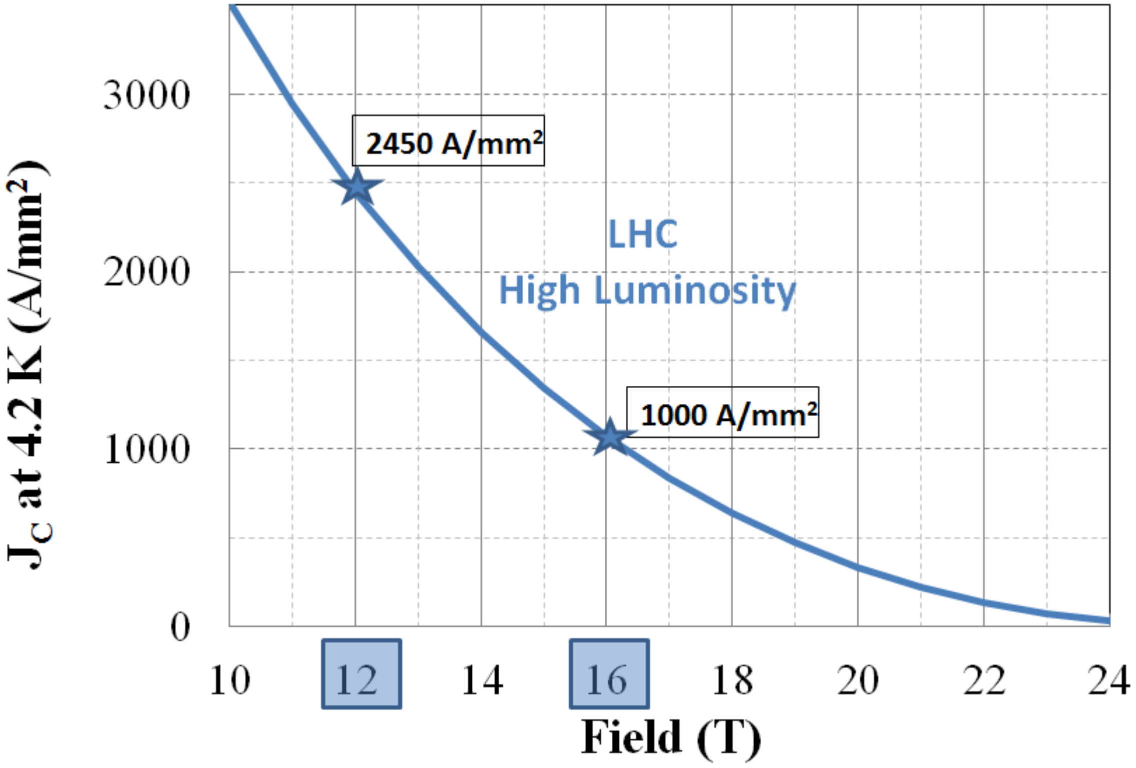


High Luminosity LHC Nb_3Sn wire

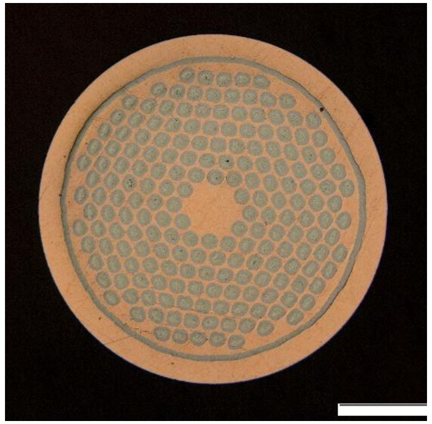
RRR > 150

Φ_{wire} = 0.7 mm, 0.85 mm

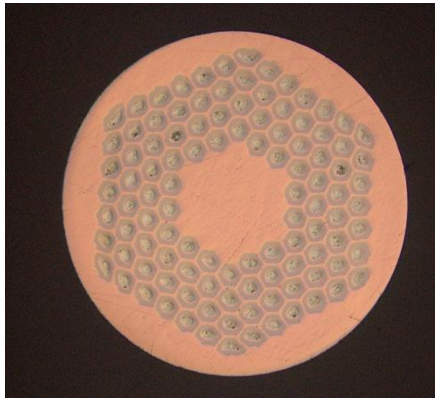
Φ_{fil} = ~ 50 μm



RRP



PIT



Superconducting Cables

- **Needed for high-current magnets**
  - Many wires in parallel
    - High current capability (10 kA – 20 kA)
    - Low inductance
- **For accelerator magnets, required**:
  - High compaction factor → **high Je**
  - **Twisting** of wires
  - **Transposition** of wires
  - Precise dimensions
  - Uniform current density
  - Controlled inter-strand resistance
  - High RRR of the strands also after cabling
- **Types of fully transposed cables:**
  - Rope, braid, Rutherford cables
- **Only Rutherford cables used – to date - in accelerator technology**

Accelerator magnets connected in series

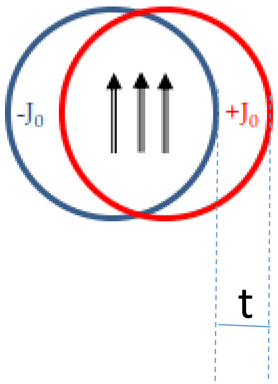
$$E = \frac{1}{2} L I^2$$

$$V = \frac{L I}{t} = \frac{2 E}{I t}$$

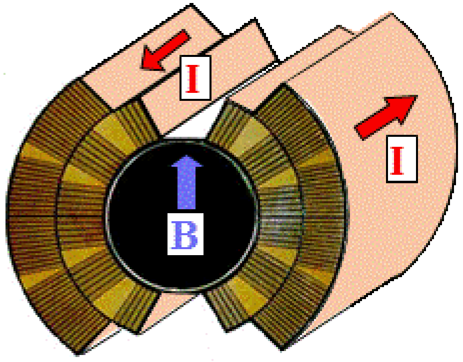
Engineering current density in dipoles

$$B = \mu_o J_e \frac{t}{2}$$

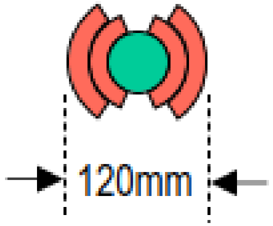
Je ~ 400 A/mm^2



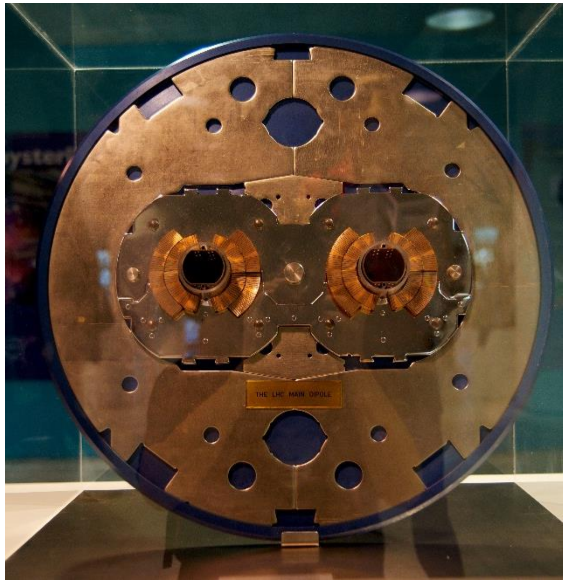
Perfect dipole field: overlapping of two cylinders with opposite currents



LHC Dipoles

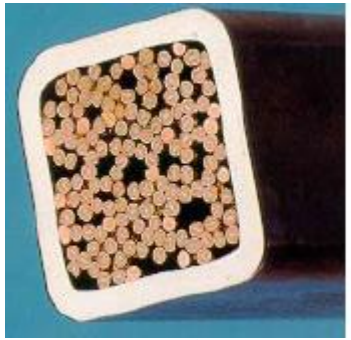


Je = 375 A/mm^2



Superconducting cables

CIC



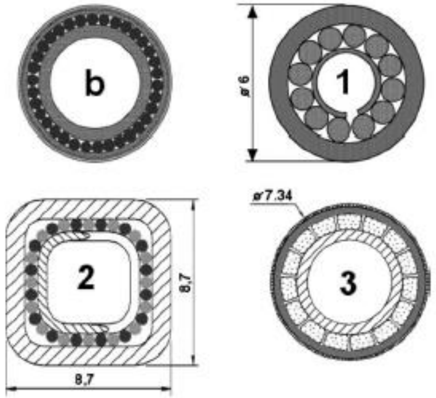
ITER magnets

Rutherford

Accelerator magnets

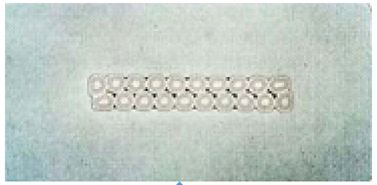
Tevatron, HERA
RHIC and LHC

Indirectly cooled

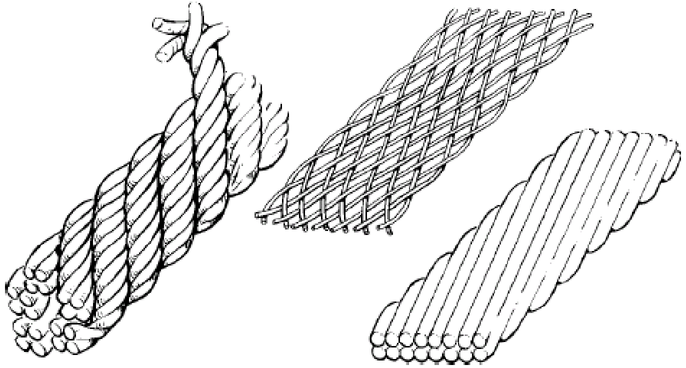


Nuclotron Type (b)
Pulsed SIS 100 magnets

Rutherford

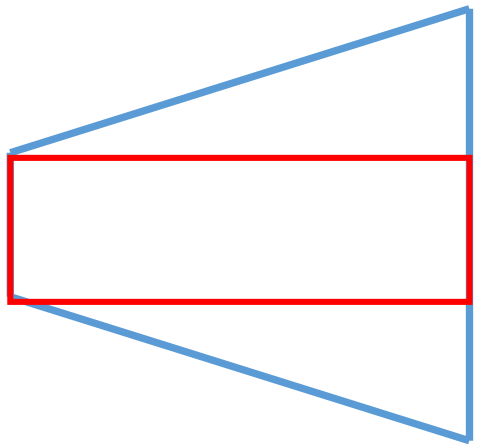


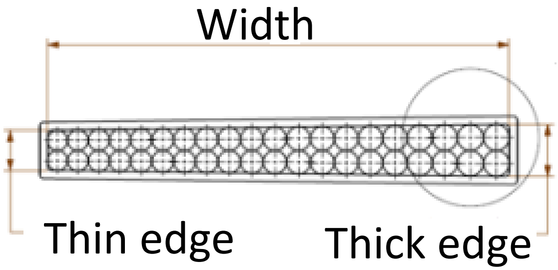
Detector magnets



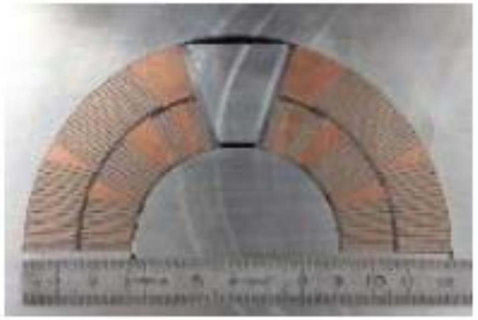
Rope, Braid and Rutherford cables

Rutherford cables





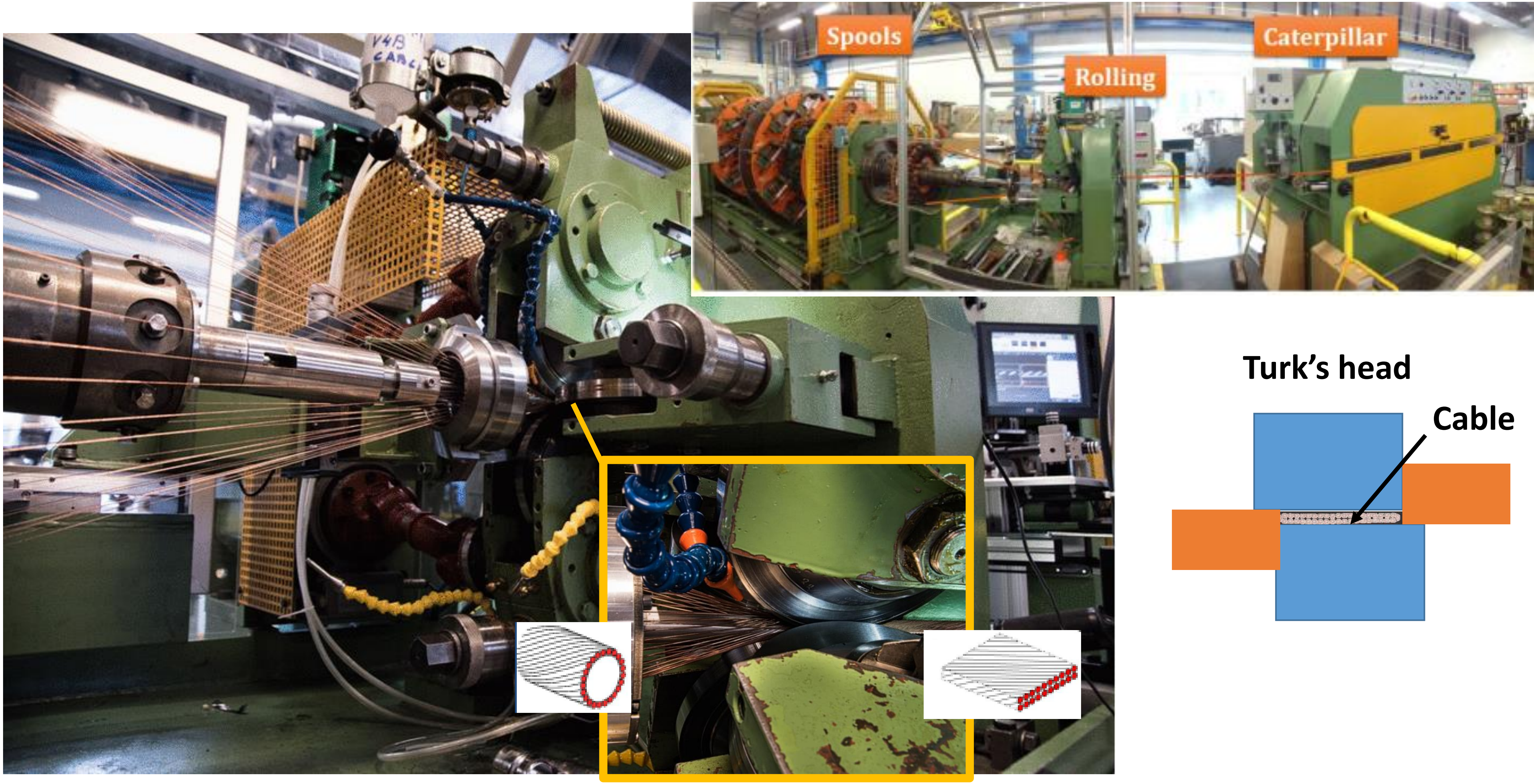
- **Multi-strand** cable (20 to 40 strands)
- Wires are twisted and compressed into a **two-layer cable**
  - Rectangular shape
  - Trapezoidal shape (for arc-shaped coil) with a trapezoidal/keystone angle < 1.5 deg



- **Tight packing** of the strands to:
  - Assure high Je
  - Prevent wire motion during magnets excitation

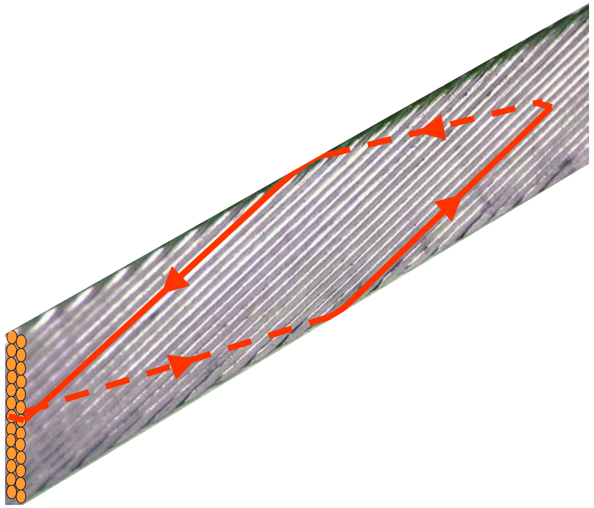
- **Low degradation of wires’ critical current** after mechanical deformation during cabling

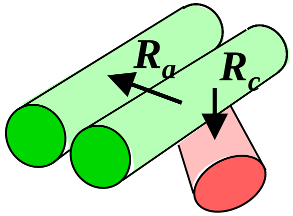
Rutherford cabling machine at CERN



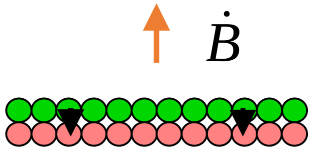
Coupling currents in Rutherford cables

Changing fields induce coupling currents in cables

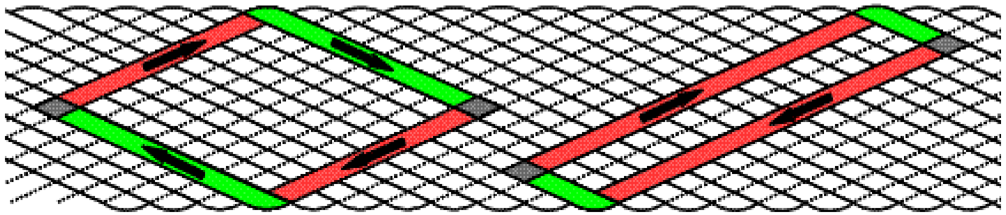




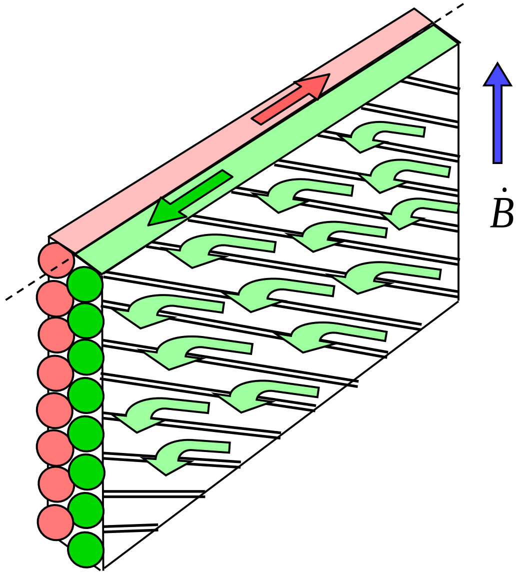
crossover resistance *Rc*
adjacent resistance *Ra*



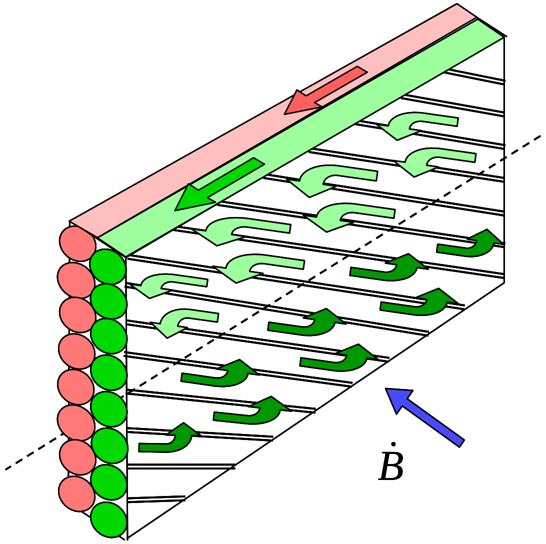
Transverse field, **cross-over resistance**



Parallel field, **adjacent resistance**



Transverse field, **adjacent resistance**



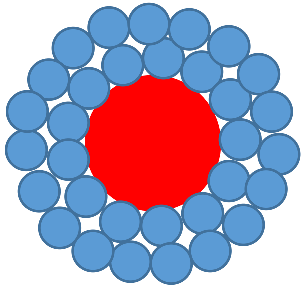
M. Wilson, JUAS School, 2015

Twisting and transposition of wires in a cable

- **Twisting** of wires in a cable
  - To cope with external magnetic field

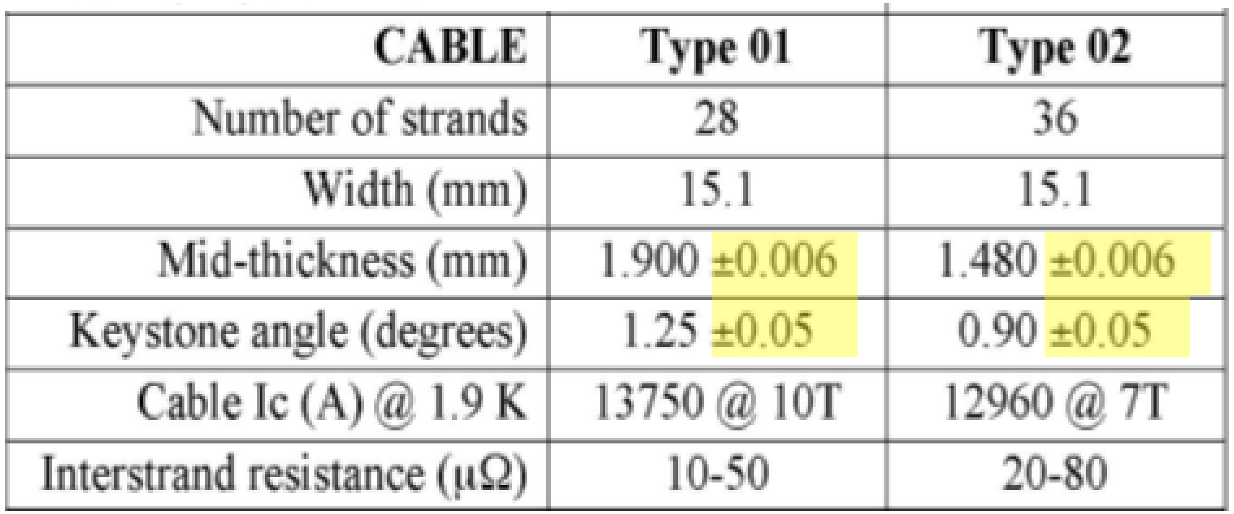
- **Transposition** of wires in cable
  - To cope with the cable self-field

  Each wire changes position with every other wire in the cable

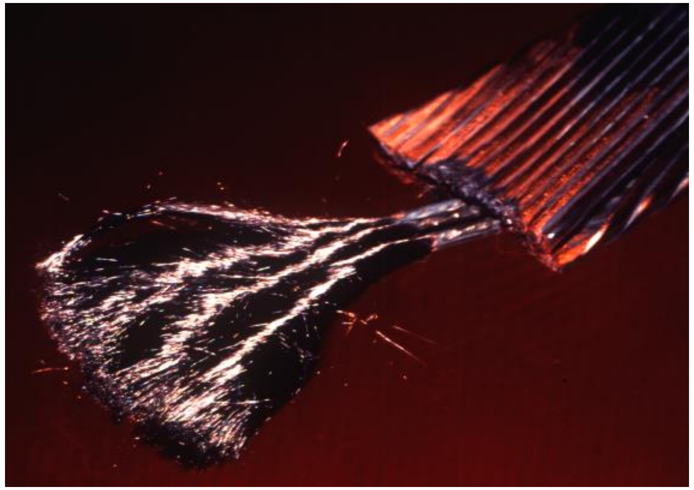


Two layer of SC wires
around a central copper core
Example of non-transposed cable

LHC Nb-Ti Rutherford Cables

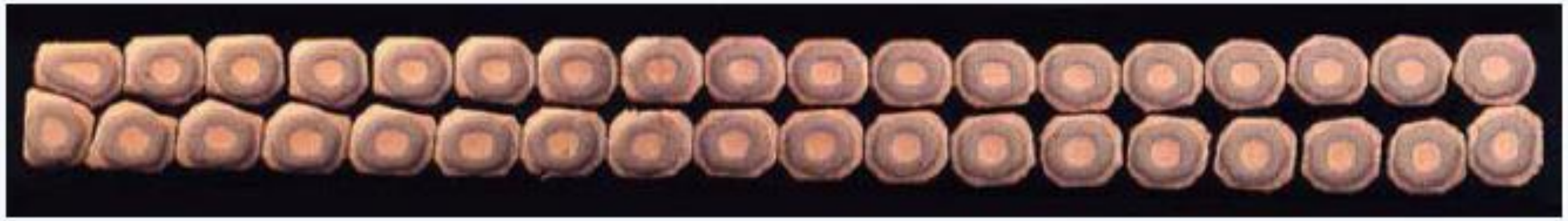


CABLE	Type 01	Type 02
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm)	1.900 ±0.006	1.480 ±0.006
Keystone angle (degrees)	1.25 ±0.05	0.90 ±0.05
Cable Ic (A) @ 1.9 K	13750 @ 10T	12960 @ 7T
Interstrand resistance (μΩ)	10-50	20-80

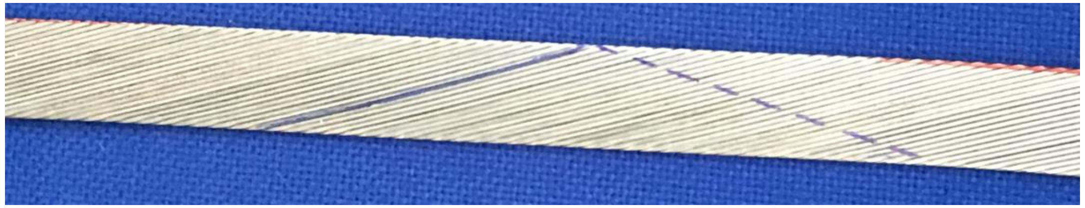


Cable compaction ~ 91 %
Wire Ic degradation ≤ 3 %

Nb-Ti LHC Main Dipole Rutherford cable – 36 strands

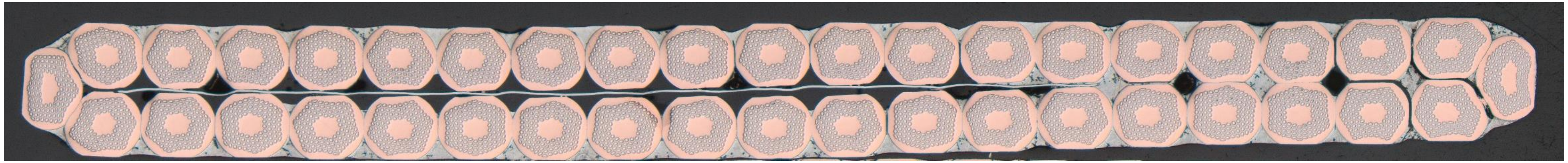


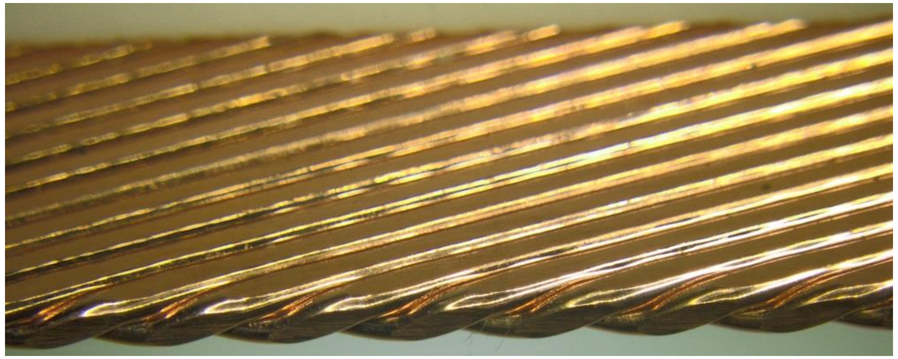
Large Hadron Collider: 7600 km (1200 tons)
Nb-Ti Rutherford cables



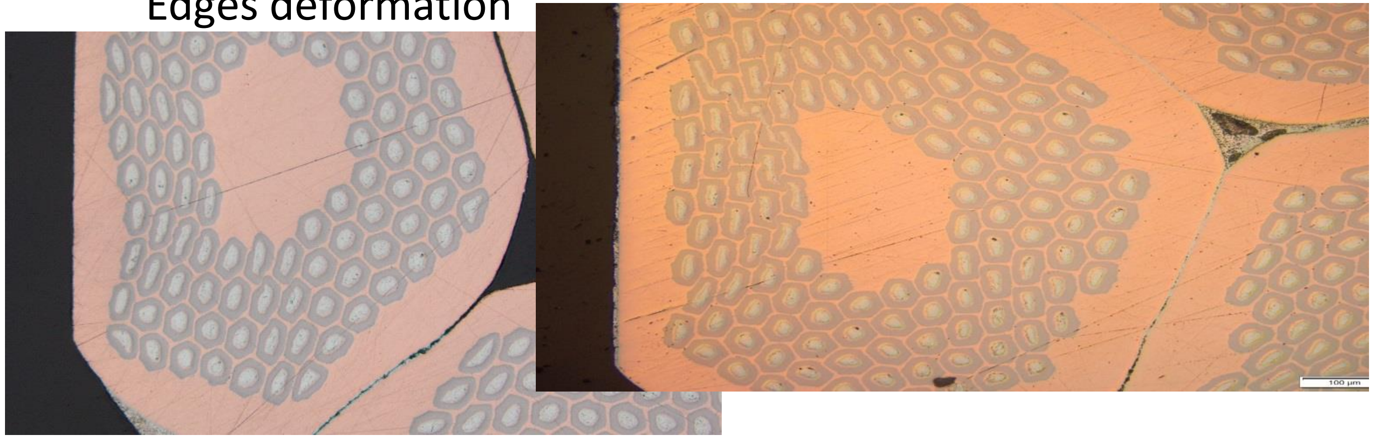
Nb_3Sn Cables

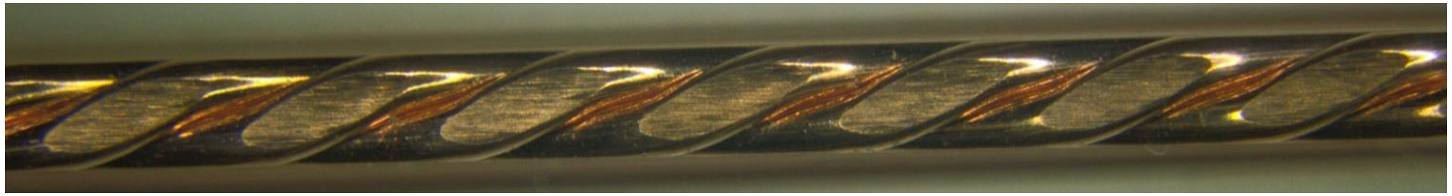
HL-LHC Cable – Forty strands



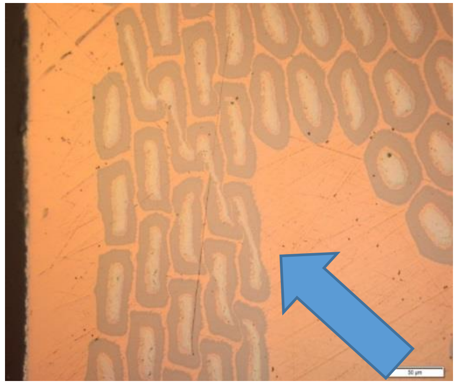


Edges deformation





Excessive shear of sub-elements



Reaction after cabling – and winding (Wind & React technology)

Sn leakage out of the Nb barrier of the filaments must be avoided !

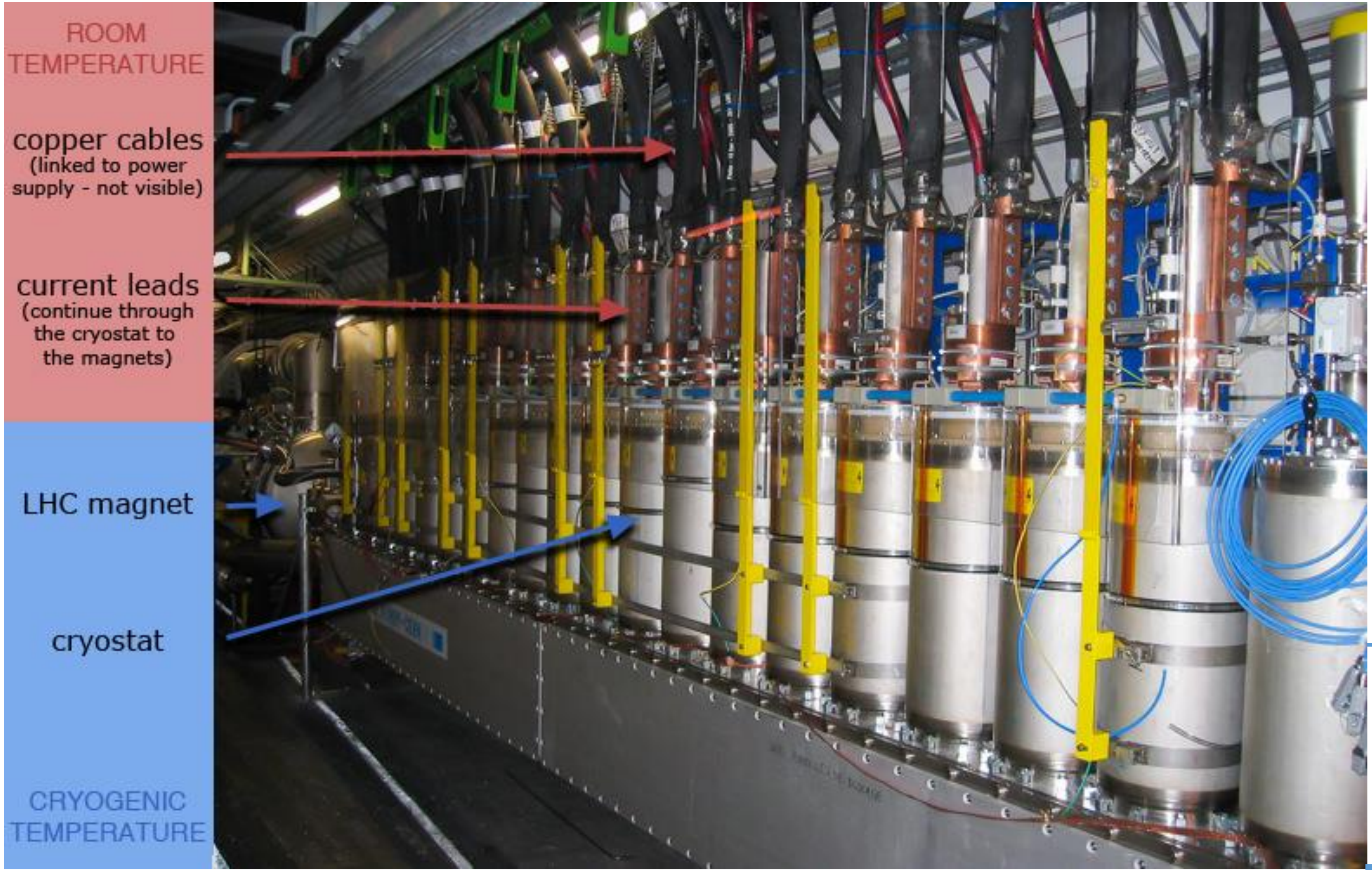
HTS Superconductors

The choice for magnetic fields > 15 T/16 T at LHe temperature

or

The choice for higher operating temperatures and lower fields

HTS in the LHC accelerator: HTS Current Leads



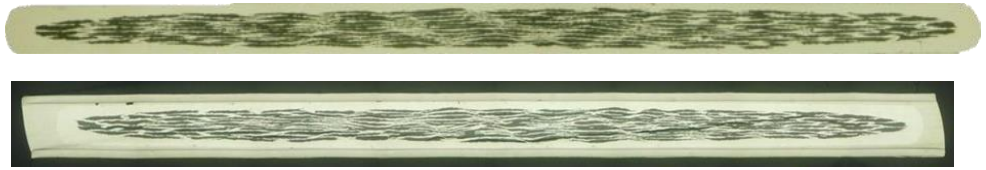
LHC: about 3 MA
More than 1000 HTS leads

50 K

BSCCO 2223
Au-Au matrix
Low k(T)

4.5 K

HTS Superconductors



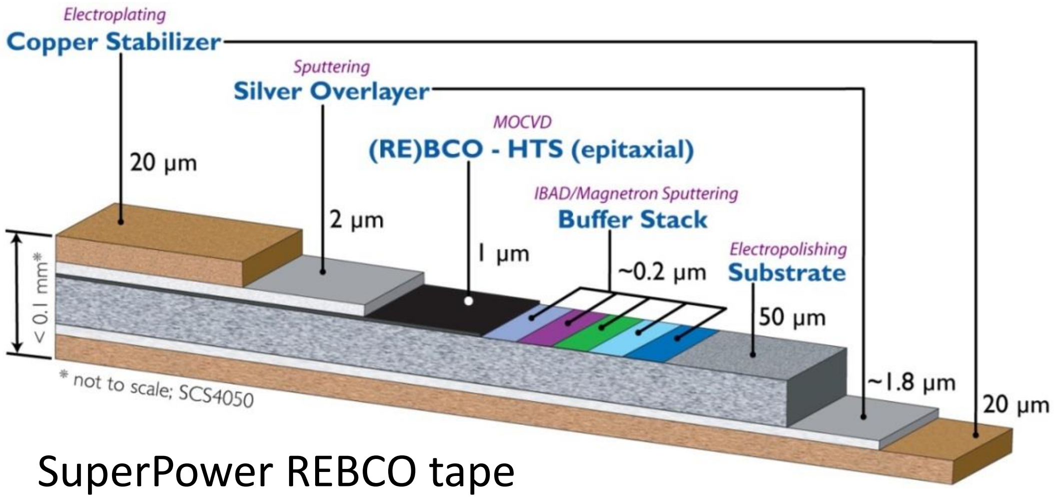
Sumitomo DI-BSCCO tape

BSCCO 2223

Multi-filamentary tape

~ 4.3 mm × 0.23 mm

~ 40 % SC



SuperPower REBCO tape

REBCO

Coated Conductor tape

~ 4 mm × 0.16 mm

~ 1% SC

OST BSCCO 2212 wire

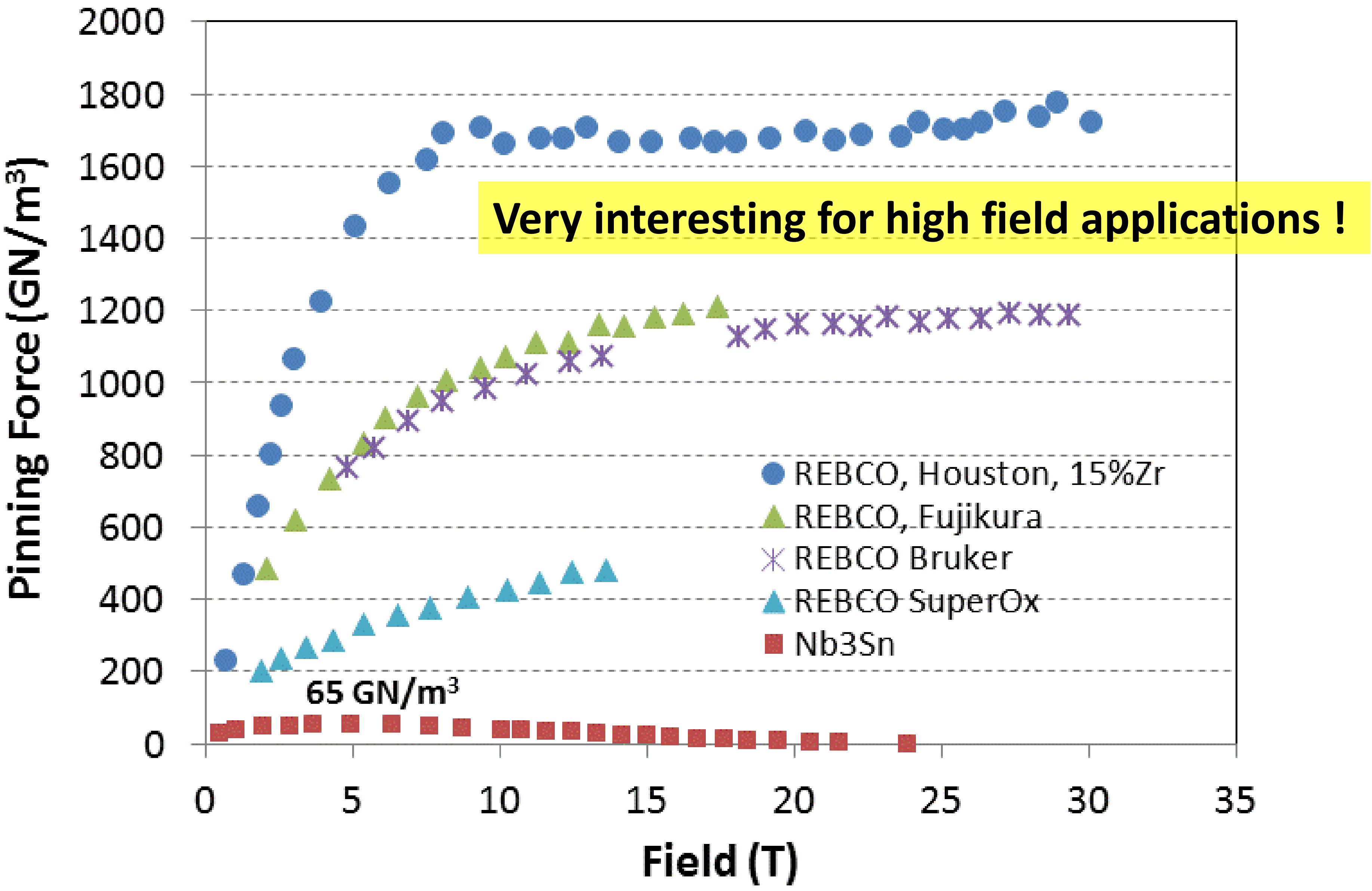
BSCCO 2212

Multi-filamentary wire

Φ = 0.8-1.4 mm

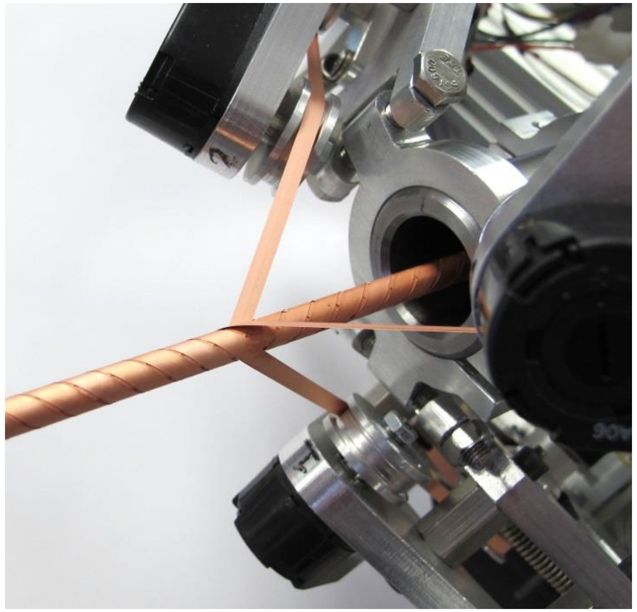
~ 30 % SC

REBCO - Pinning

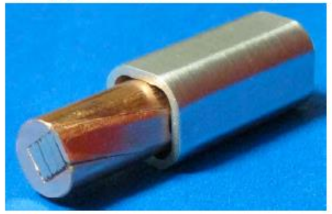


Very interesting for high field applications !

REBCO Cables

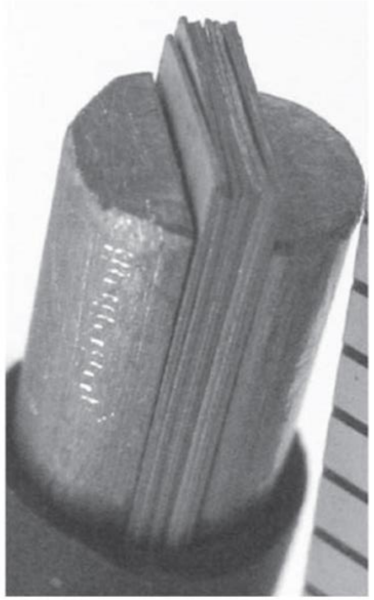


12 mm x 12 mm CICC
(copper diameter 9.5 mm)



40 YBCO tapes in a copper
diameter 9.5 mm.

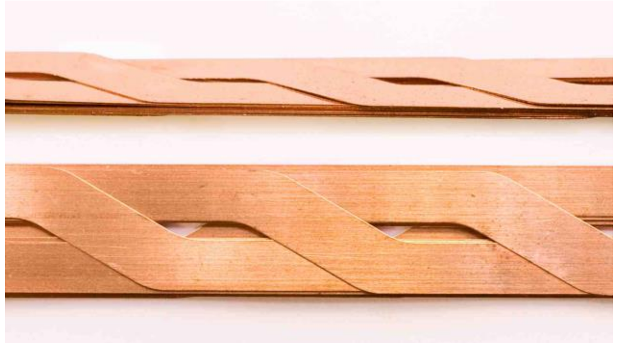
20 YBCO tapes in each helical
groove in a copper diameter
9.5 mm.

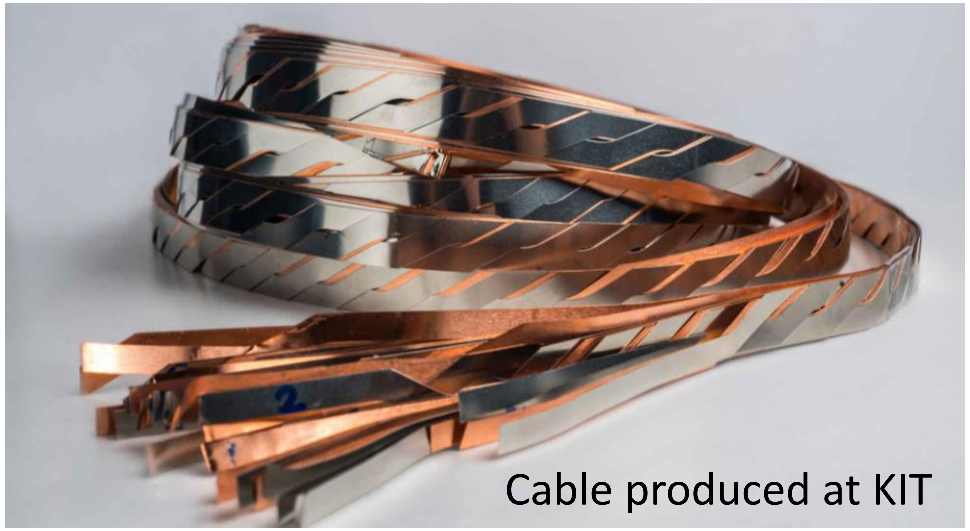


REBCO prototype **cables** studied for **fusion technology**

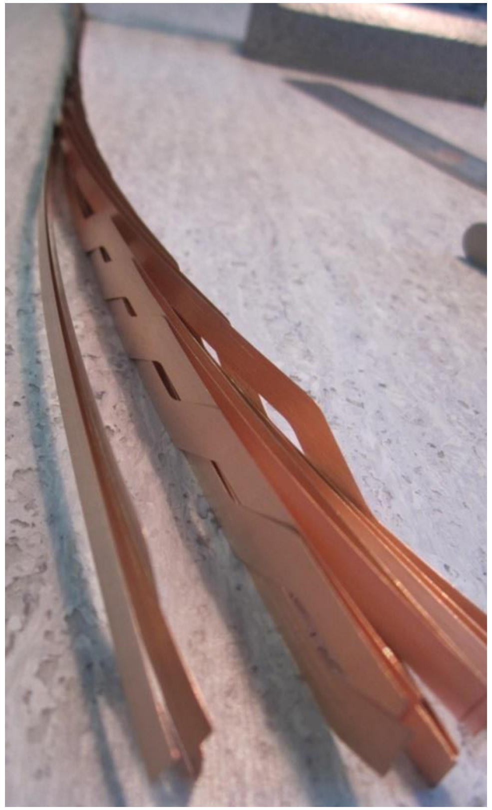
The Je of these cables is insufficient for accelerator technology

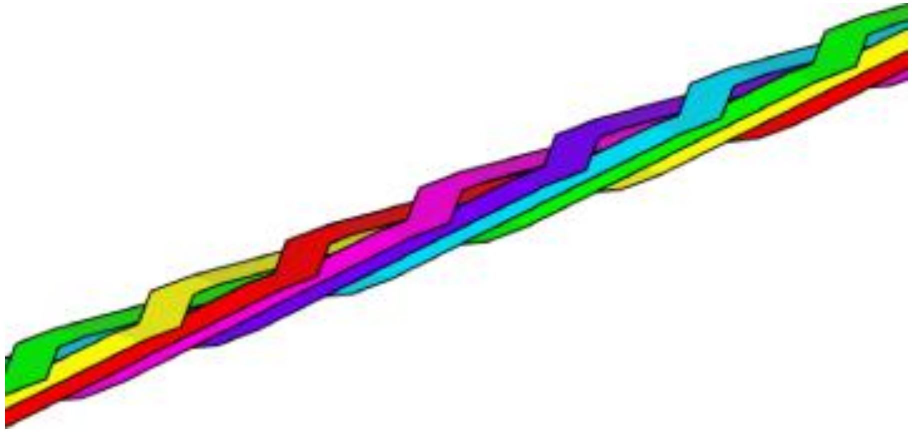
HTS Roebel cable

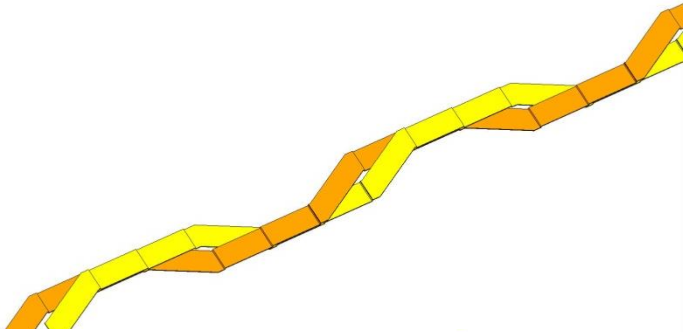


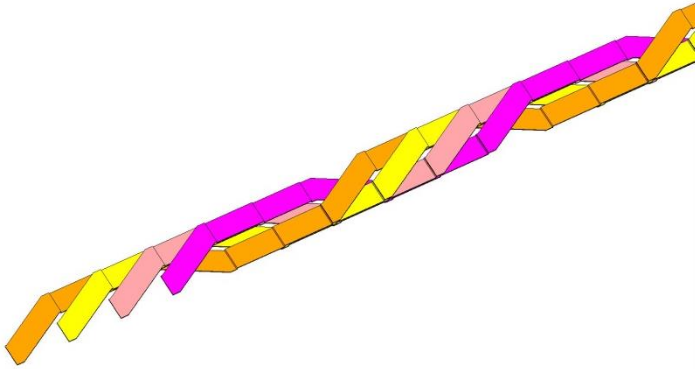


Cable produced at KIT

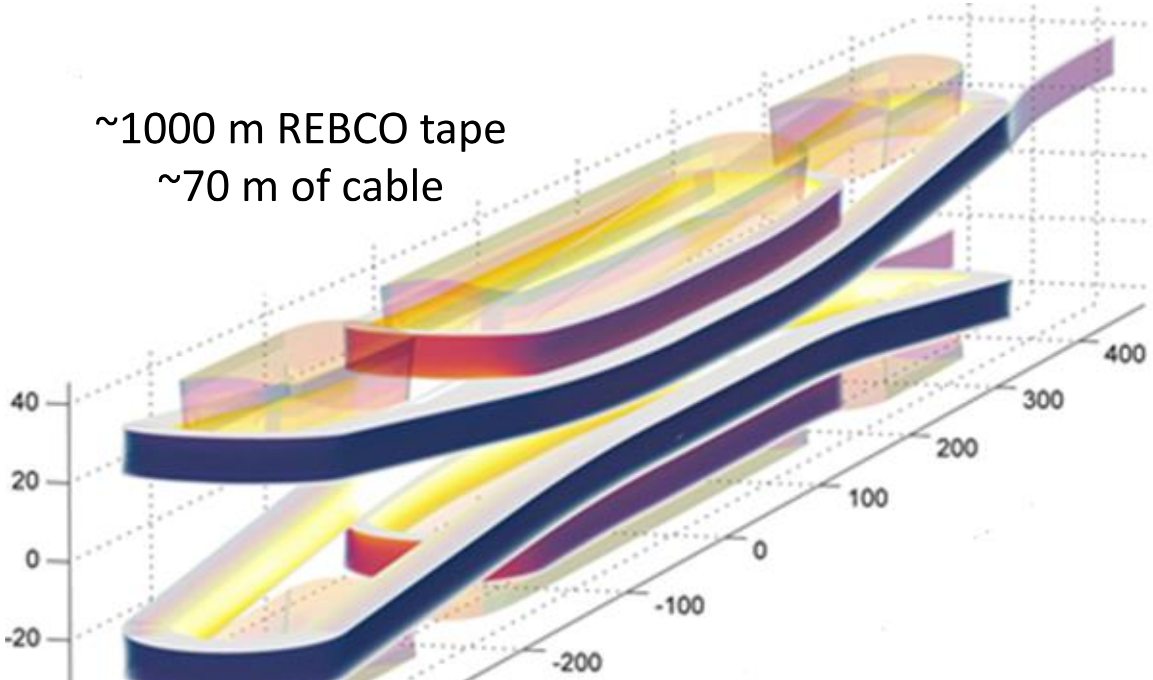








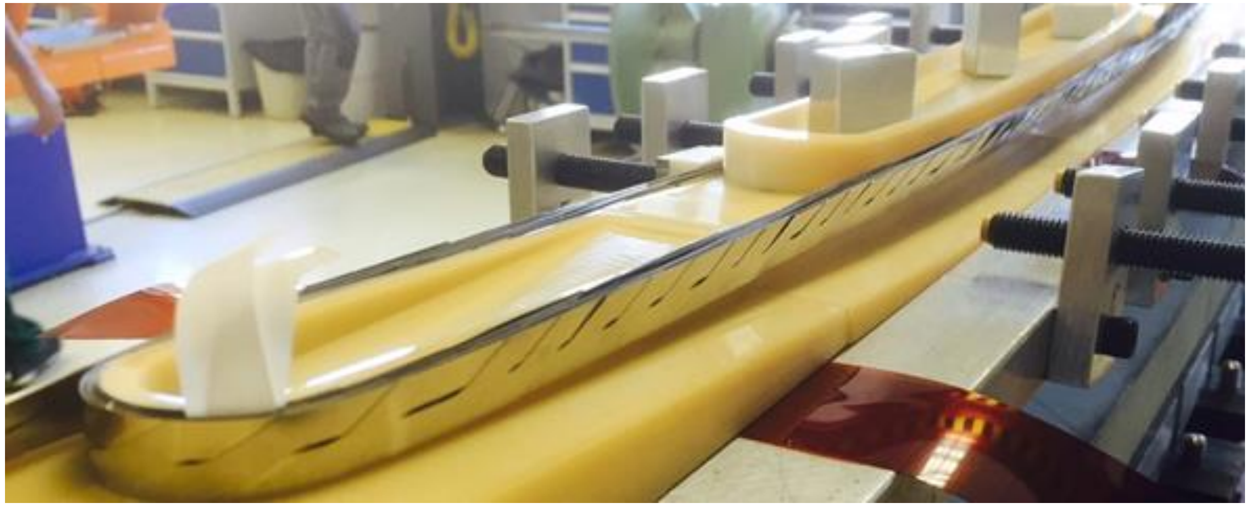
Model magnets



~1000 m REBCO tape
~70 m of cable

Aperture = 40 mm

5 T in a background field of 15 T



Conductor for future circular colliders

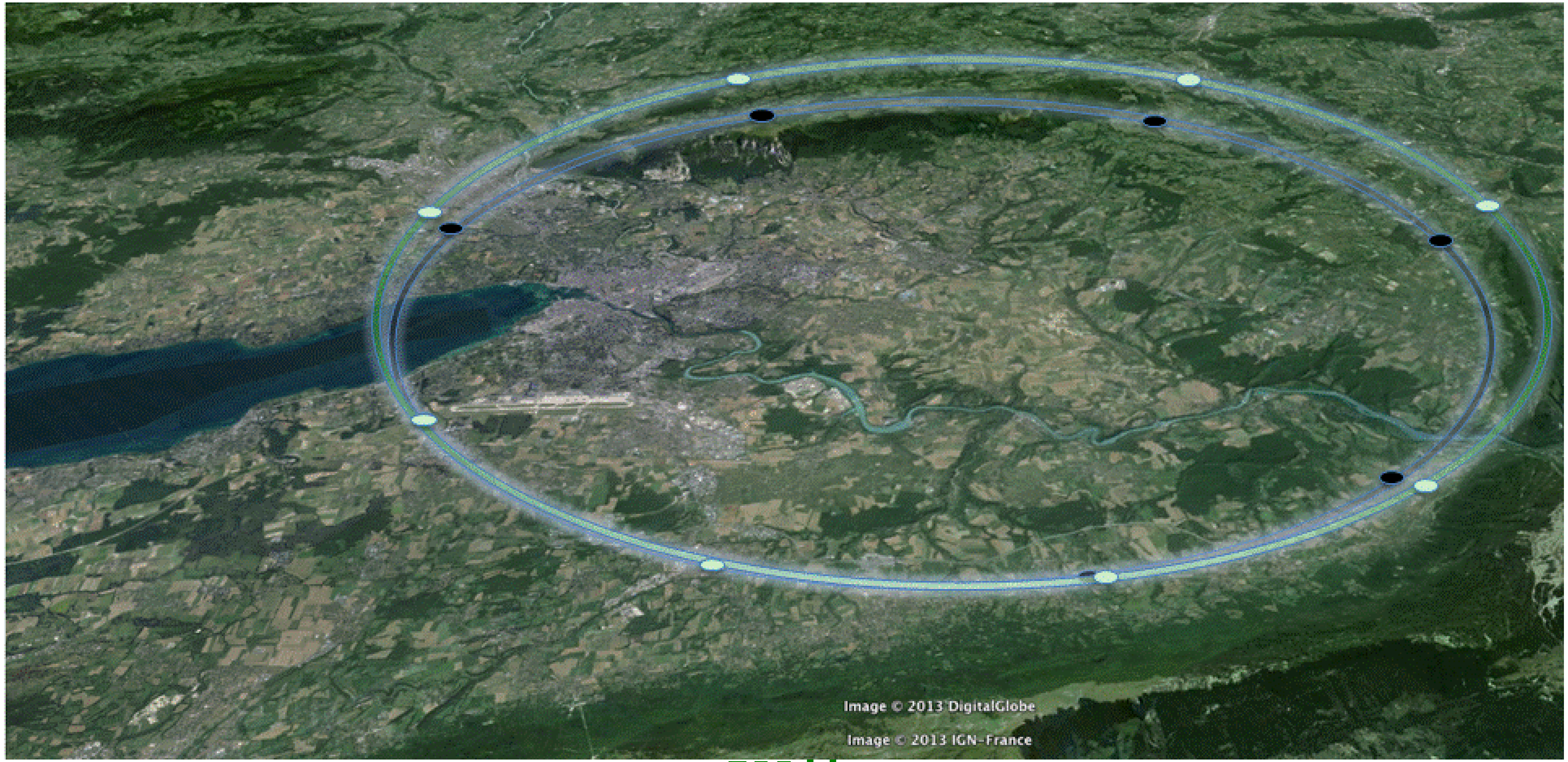
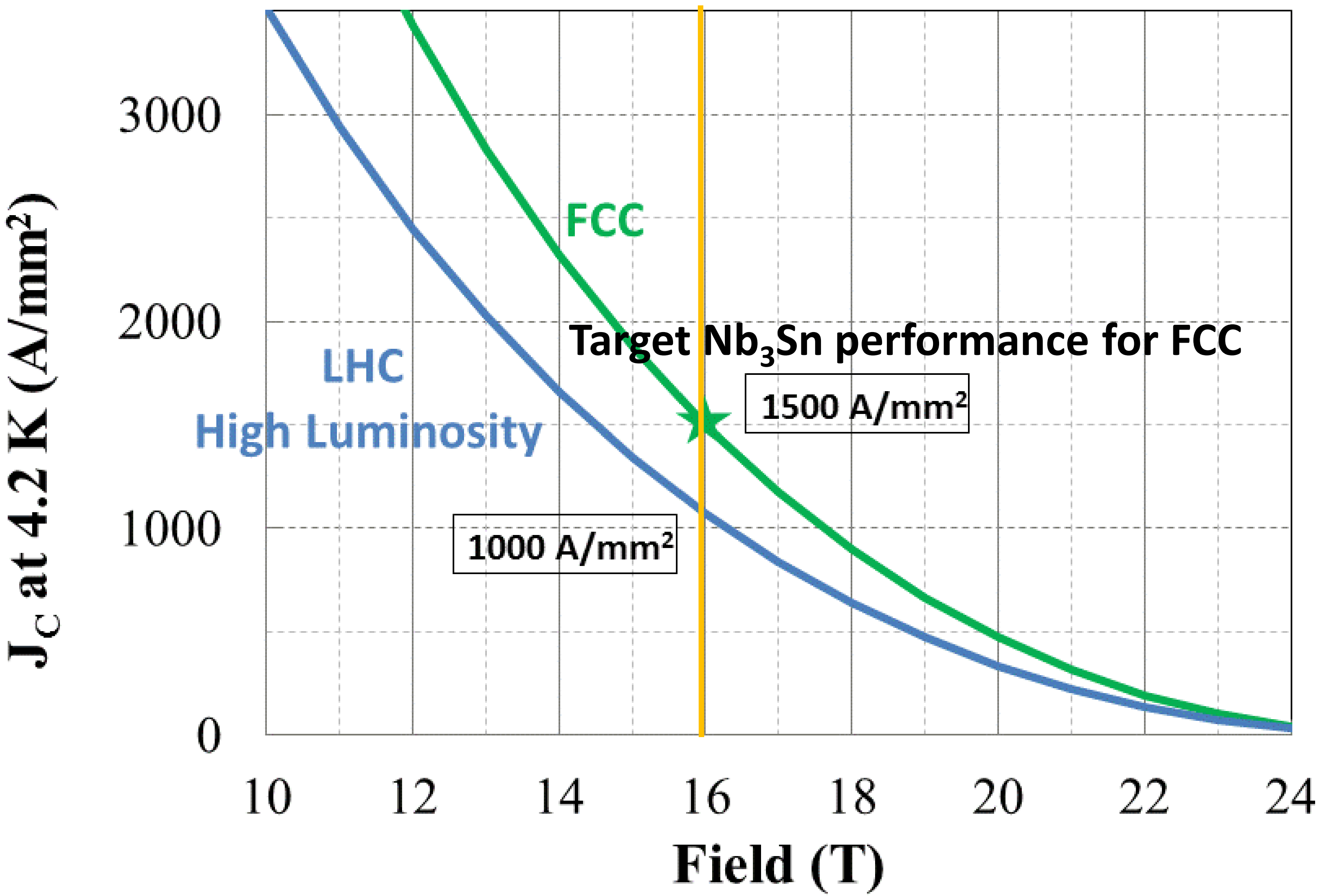


Image © 2013 DigitalGlobe

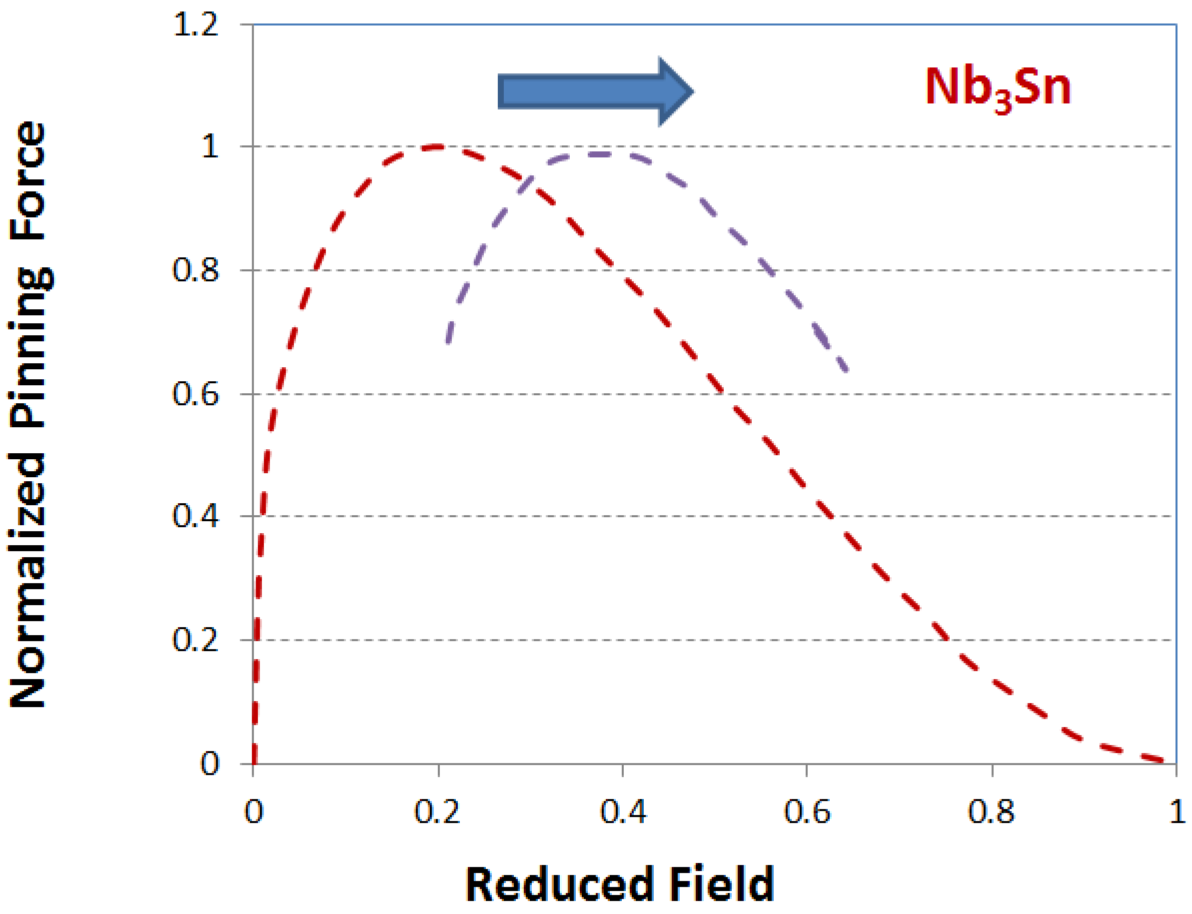
Image © 2013 IGN-France

LHC	**FCC-hh**	**FCC-hh**
27 km, 8.33 T	100 km, 16 T	80 km, 20 T
14 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1200 tons Nb-Ti	6000 tons Nb_3Sn	9000 tons LTS
200 kg HTS	3000 tons Nb-Ti	2000 tons HTS

Conductor performance for the FCC Collider



The FCC Collider



Jc ∝ GBD/d

d = grain diameter
GBD = Grain boundaries Density

Conclusions

- We reviewed the properties of superconductors for high field applications: Nb-Ti, Nb_3Sn and REBCO

  Nb-Ti is the workhorse material

  Nb_3Sn is used in fusion technology. It will be used for the first time in accelerator technology for HL-LHC. It is complex, and it replaces Nb-Ti for fields above 10 T

  REBCO is extremely interesting and promising, but high field magnet technology is still at a development stage

  MgB_2 and **iron based** materials are intriguing

- The FCC study re-launched an exiting development for Nb_3Sn superconductor, waiting for HTS technology be mature

A magnet will never perform better than its conductor