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INFN
Istituto Nazionale di Fisica Nucleare

THE SUPERCONDUCTING THIN SOLENOID FOR IDEA. A TRADITIONAL DESIGN OR A STEP TORWARD NEW TECHNOLOGIES?

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On behalf of the Applied Superconductivity Group of INFN-Genova

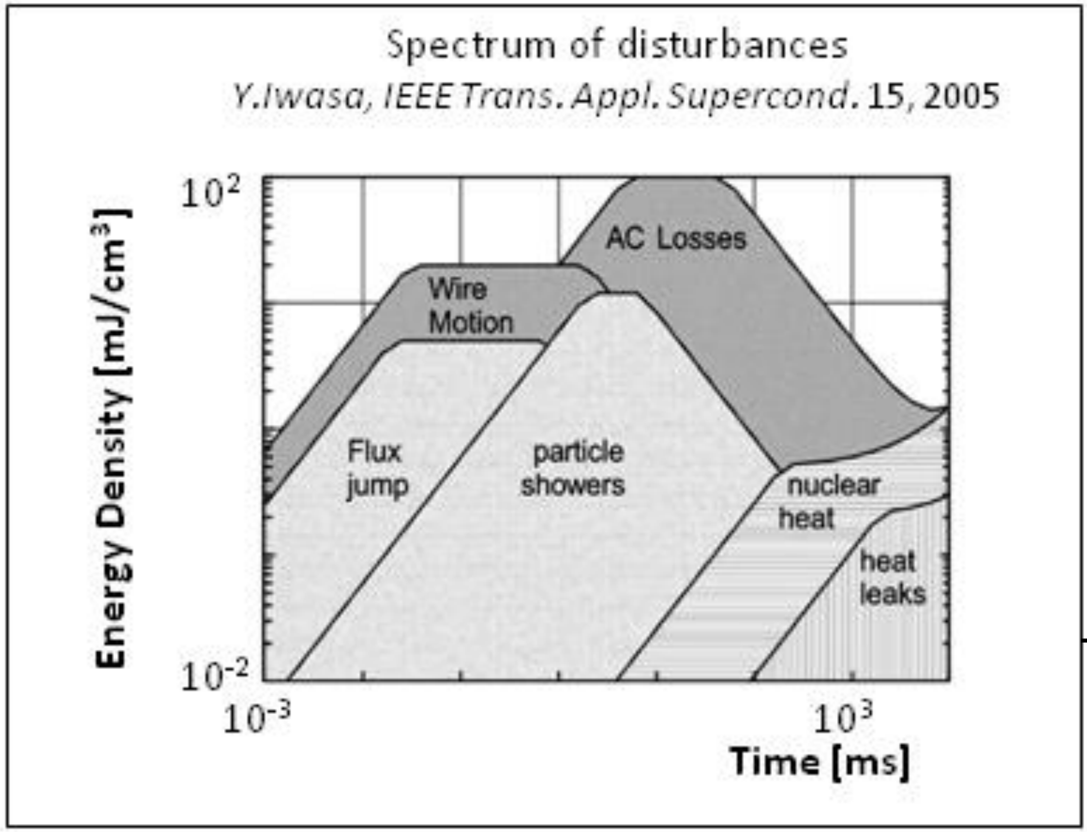
SUPERCONDUCTING MAGNETS FOR PARTICLE DETECTORS

Main characteristics:

- Large volume
- Moderate magnetic field (0.5 to 2 T)
- Transparency to particles is often required (thin magnets)
- Generally, solenoidal configuration

An important feature of superconducting magnets is **stability**

Stability is related to the release of energy that a magnet can withstand without quenching


Spectrum of disturbances

Y.Iwasa, IEEE Trans. Appl. Supercond. 15, 2005

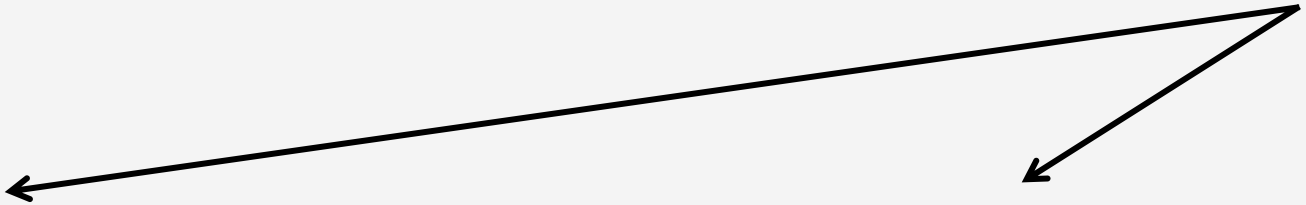
$$\nabla(k_{cond}\nabla T) + \rho_{cond}J^{2} + g - h = c_{cond}\frac{\partial T}{\partial t}$$

Joule dissipation

cooling power

Cryogenic stability

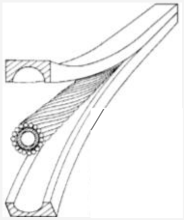
$$\rho_{cond} J^2 + g \leq h$$



Low resistivity normal metal matrix (in parallel to superconductors) and good cooling

Magnets in liquid Helium pool

Forced flow magnets



OMEGA magnet (CERN)

Adiabatic stability

The heat generation term must be limited to a maximum permissible level

$$\Delta e_{max} = \int_{T_{op}}^{T_{max}} c_{cond} \, dT$$

Δe_{max} is the energy density margin

T_{max} is the temperature at which the superconductor undergoes the transition to the normal state (it depends on B and J)

Typical value of $T_{max} - T_{op}$ for NbTi is between 2 K and 3 K

Thin solenoids

Thin solenoids are based on adiabatic stability

⇩

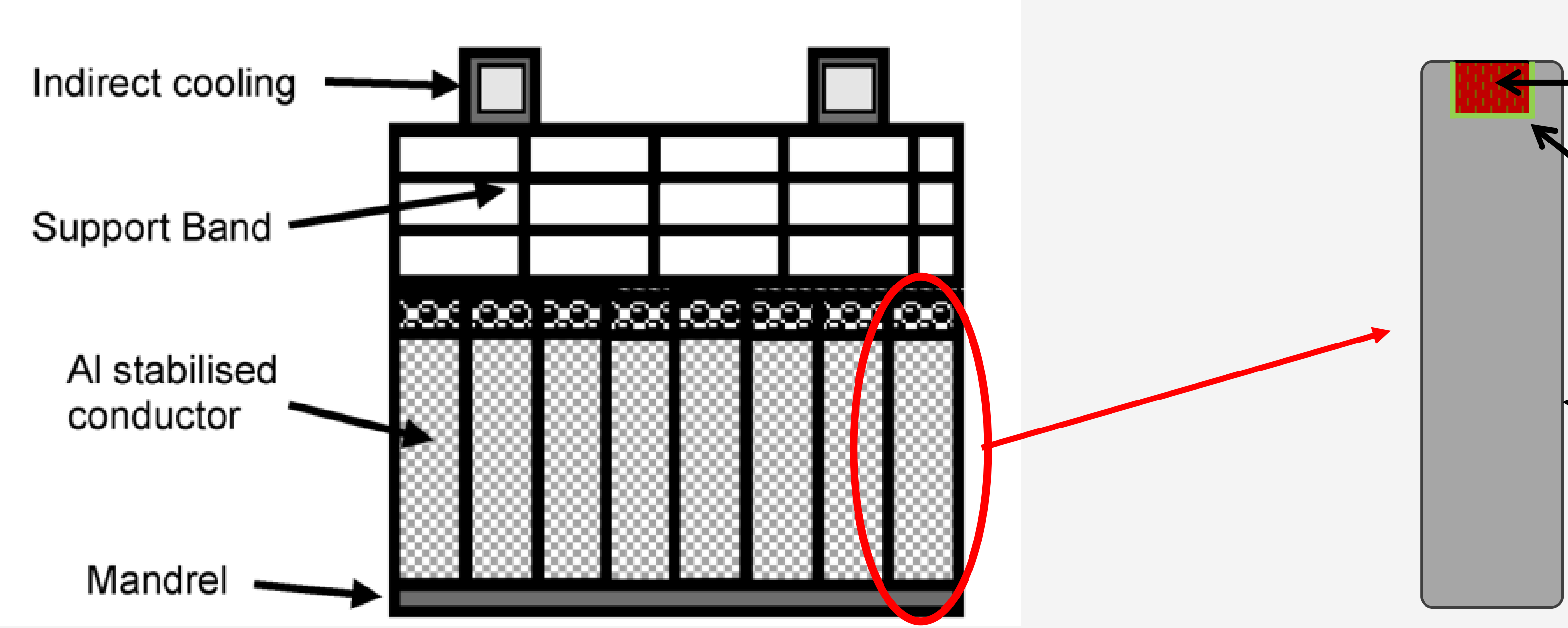
Aluminium stabilised NbTi conductors

NbTi is ductile, relatively cheap and robust (J_C is not affected by mechanical stress)
Aluminium: Low density, high radiation length, low resistivity at 4.2 K (RRR>2000)

Pure Aluminium in parallel to the superconducting composite:

- increases the conductor thermal capacity per unit length
- limits the dissipation in case of local transition to the normal state
- limits the magnet weight
- allowing positioning calorimeters outside the magnet

Thin solenoids

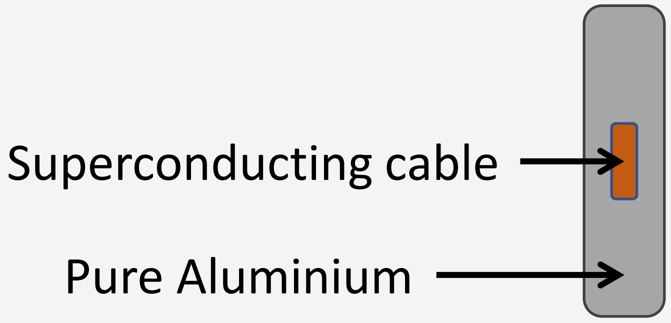


Schematic of the CELLO magnet

Thin solenoids

Later, aluminium stabilised conductors have been manufactured by co-extrusion, in such a way that the superconducting cable is embedded in pure aluminium matrix

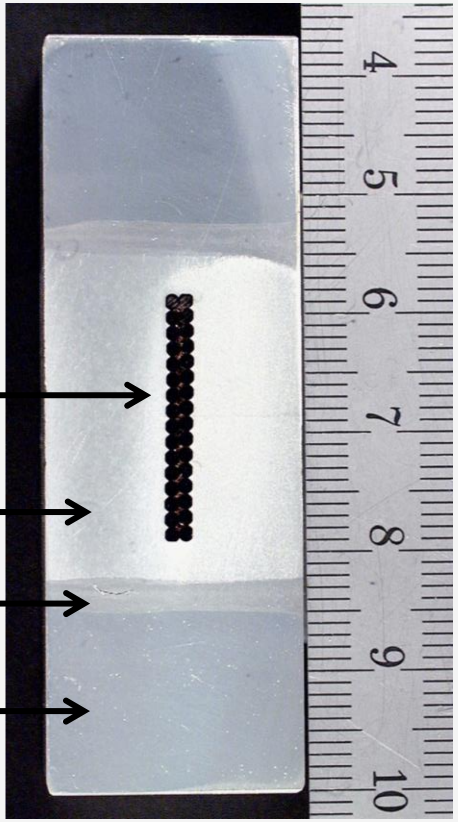
The co-extrusion technology was applied for the first time in the CDF magnet (FERMILAB) in 1984



Thin solenoids

CMS conductor

Aluminium stabilised cable reinforced with EBW Aluminium alloy



Superconducting cable

Pure Aluminium

EB welding

Aluminium alloy

Thin solenoids

In some detector magnet, pure aluminium is replaced by high strength, low resistivity aluminium-nickel alloys.

ATLAS central solenoid [A.Yamamoto et al. NIM A 584, 2008, 53–74]

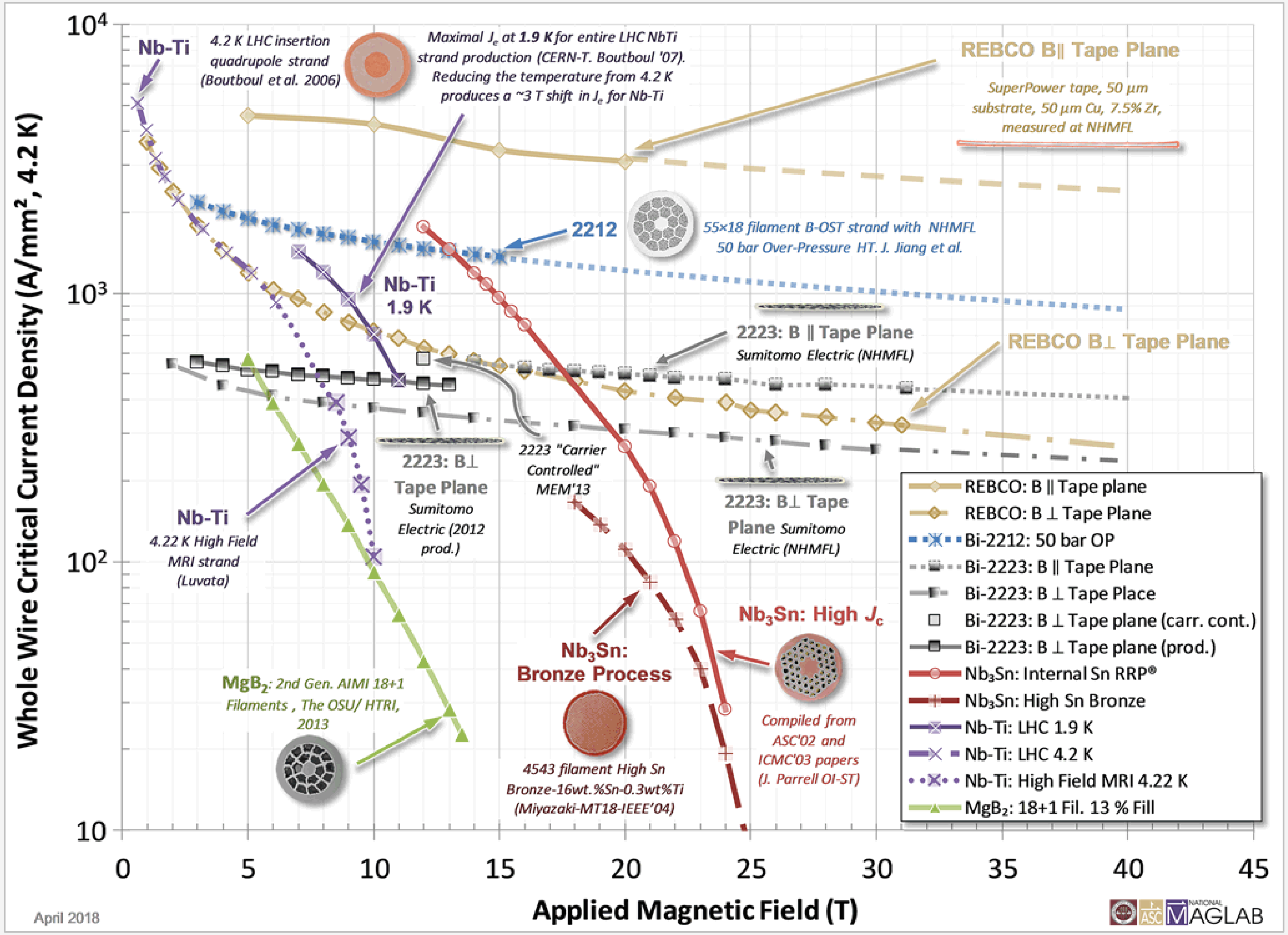
Aluminium stabilisation is a terrific solution that has been applied to a large number of detector magnets.

However, fabrication of conductors requires cabling and co-extrusion.

Co-extrusion is an expensive and delicate industrial process.

Very few firms have the expertise to perform co-extrusion.

Would it make sense to use other superconductors?



https://nationalmaglab.org/magnet-development/applied-superconductivity-center

Technical superconductors

REBCO (tape) $T_c = 92\ K$

BiSCCO 2223 (tape – Ag matrix) $T_c = 108\ K$

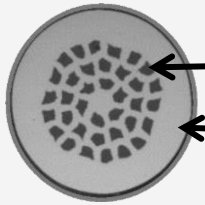
BiSCCO 2212 (Ag matrix) $T_c = 96\ K$

Nb_3Sn $T_c = 18\ K$

MgB_2 $T_c = 39\ K$

MgB_2 is more expensive than NbTi but much cheaper respect to REBCO and BiSCCO

It is produced by reacting the precursors powders at about 700°C for few minutes



MgB_2 filaments

Metallic matrix (Ni, Ni-Cu or Ti)

In situ: wires are prepared by powder-in-tube method using the precursors. MgB_2 is then obtained inside the wire by suitable heat treatment

Ex situ: wires are prepared by powder-in-tube method directly using MgB_2 powders.

MgB_2 has **low reversibility field** B_{irr} (if $B \geq B_{irr}$ then $J_c = 0$)

Pure MgB_2: $B_{irr} \approx 12\ T$

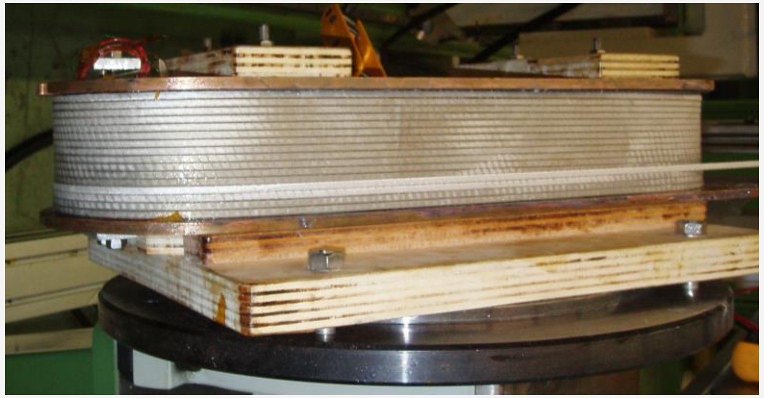
Doping increases B_{irr}

But detector magnets must not generate high magnetic field

Generally $B < 4\ T$

Like all technical superconductors except NbTi, MgB_2 is **brittle**:
for a given MgB_2 composite conductor, a critical bending radius does exist (order of 10 cm for a 1 mm wire).

Not an issue for large magnets!



Winding of a racetrack coil with ex-situ MgB_2 tape

MgB$_2$ would allow operating the magnet at $\boldsymbol{T > 10\ K}$ ($T_c = 39\ K$)

More efficient cryogenics

Higher COP

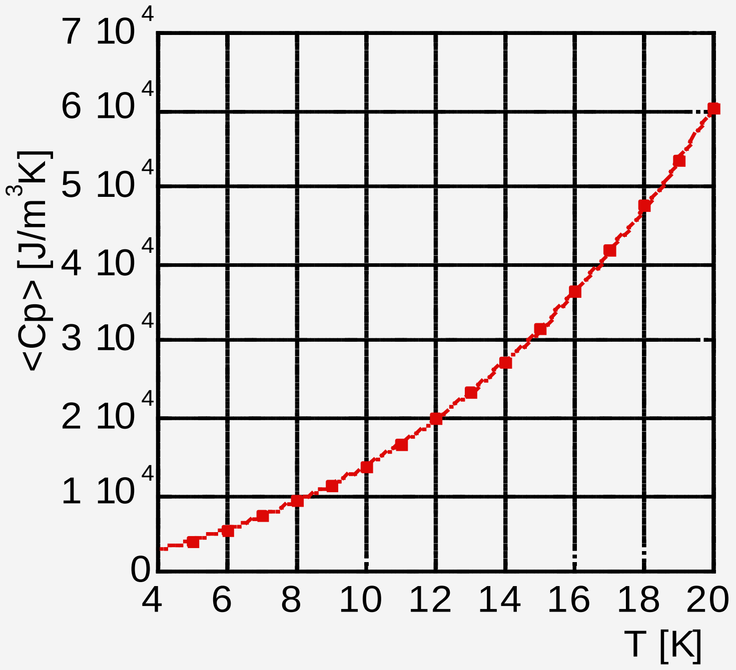
Better conduction cooling

$$\frac{K_{Al6061}@15\ K}{K_{Al6061}@4.2\ K} \approx 4$$

Higher energy density margin

$$\Delta e_{max} = \int_{T_{op}}^{T_{max}} c_{cond}\, dT$$

$$c_{cond} \propto \left(\frac{T}{\theta_D}\right)^3$$



Aluminium matrix is not necessary for stabilization.
It can be necessary/useful for quench protection.

MgB_2 conductors are **already used to wind magnets**.

Open MRI based on cryogen free magnet wound with magnesium diboride tapes (ASG Superconductors)

First proposals about MgB_2 conductors coupled with aluminium were related to space applications due to low weight requirement

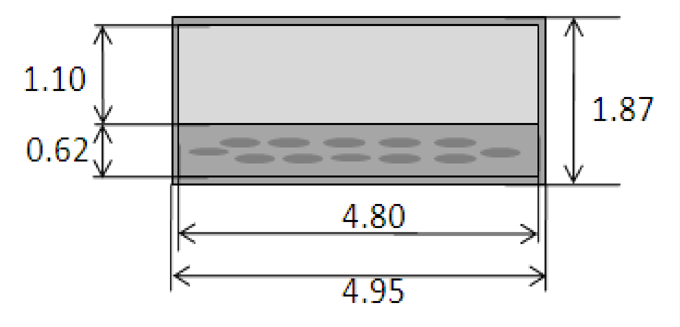
P. Spillantini,
Superconducting magnets and mission strategies for protection from ionizing radiation in interplanetary manned missions and interplanetary habitats
Acta Astronautica, 68 (9–10), 2011, 1430-1439

R. Battiston, W. J. Burger, V. Calvelli, V. I. Datskov, S. Farinon, and R. Musenich
Superconducting Magnets for Astroparticle Shielding in Interplanetary Manned Missions
IEEE Trans. on Appl. Supercond., 23 (3), 2013, 4101604

SR2S Space Radiation Superconducting Shield

EU FP7 project to study superconducting shields to protect astronauts from space radiation

Conductor: **Titanium clad MgB_2 tape + Aluminium strip**

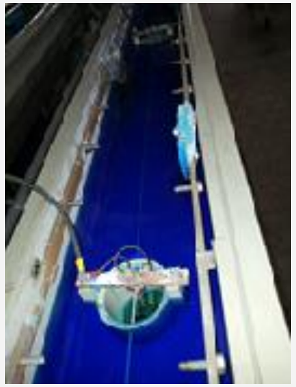


Ti/MgB_2 ratio 2.7/1
75 µm thick insulation
Total conductor cross section: 9.25 mm^2
Average mass density : 3000 kg/m^3

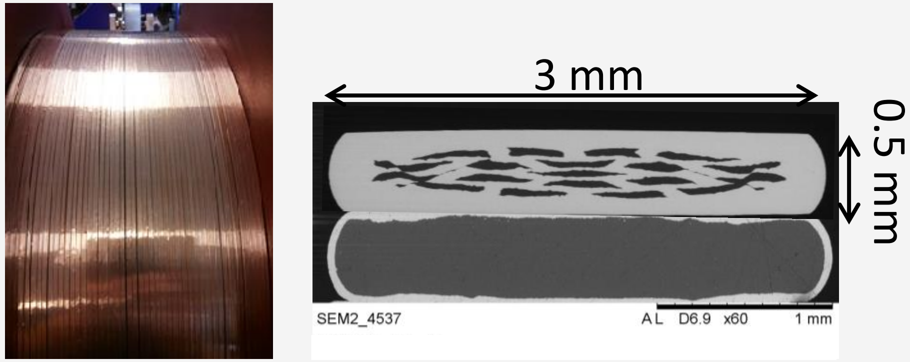
R. Musenich et al., “Ti–MgB2 Conductor for Superconducting Space Magnets”, IEEE Trans on Appl. Supercond26 (4), 2016

Development of the **SR2S conductor prototype**


360 m Ti-MgB_2

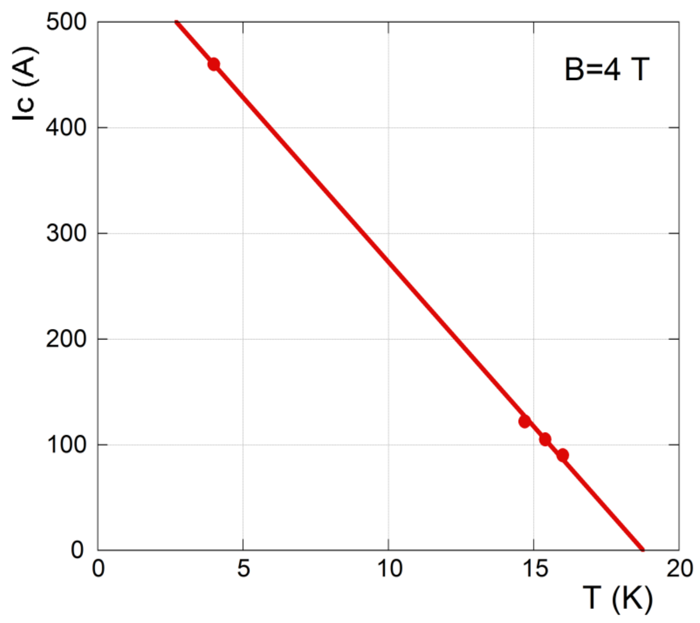

Ti-MgB_2 tape during copper plating


Copper plated Ti-MgB_2 tape



Cu-Ti-MgB_2 tape

INFN Istituto Nazionale di Fisica Nucleare + ~~Columbus Superconductors~~ → now ASG SUPERCONDUCTORS

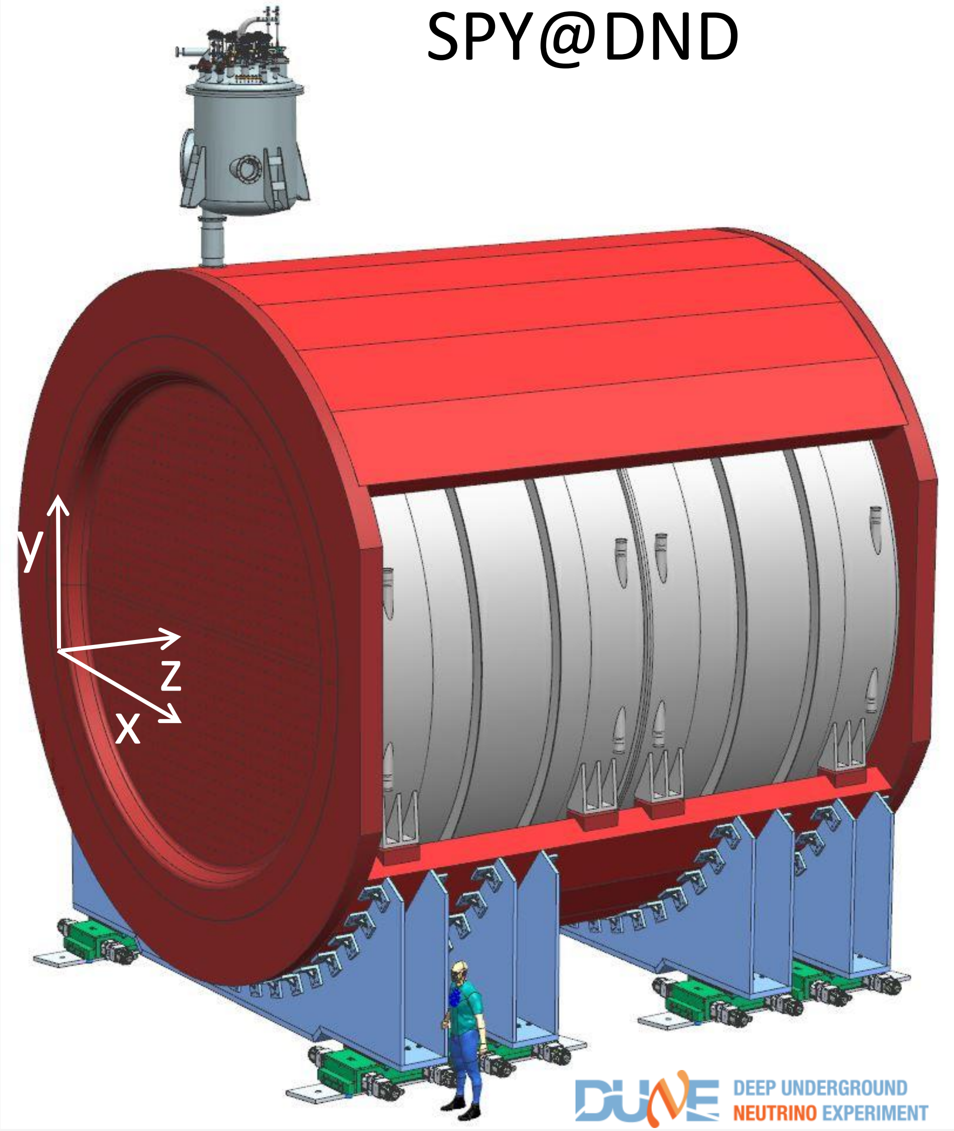


Problems occurred during aluminium tape soldering due to different thermal contractions.
Solution was identified but, due to tight schedule and limited funds, no further attempts were made to solder the aluminum tape.

INFN-Genova has started an **R&D on application of Magnesium Diboride to future detector magnets**

The idea of using MgB_2 for detector magnets arose during the preliminary design of the large solenoid for the DUNE (Deep Underground Neutrino Experiment) near detector, triggered by the current lack of availability of NbTi, aluminum stabilized conductors.

Large solenoid for the DUNE near detector



I_{op} = 4585 A

B_{center} = 0.52 T

J_e = 35 A/mm²

6 coils X 120 turns

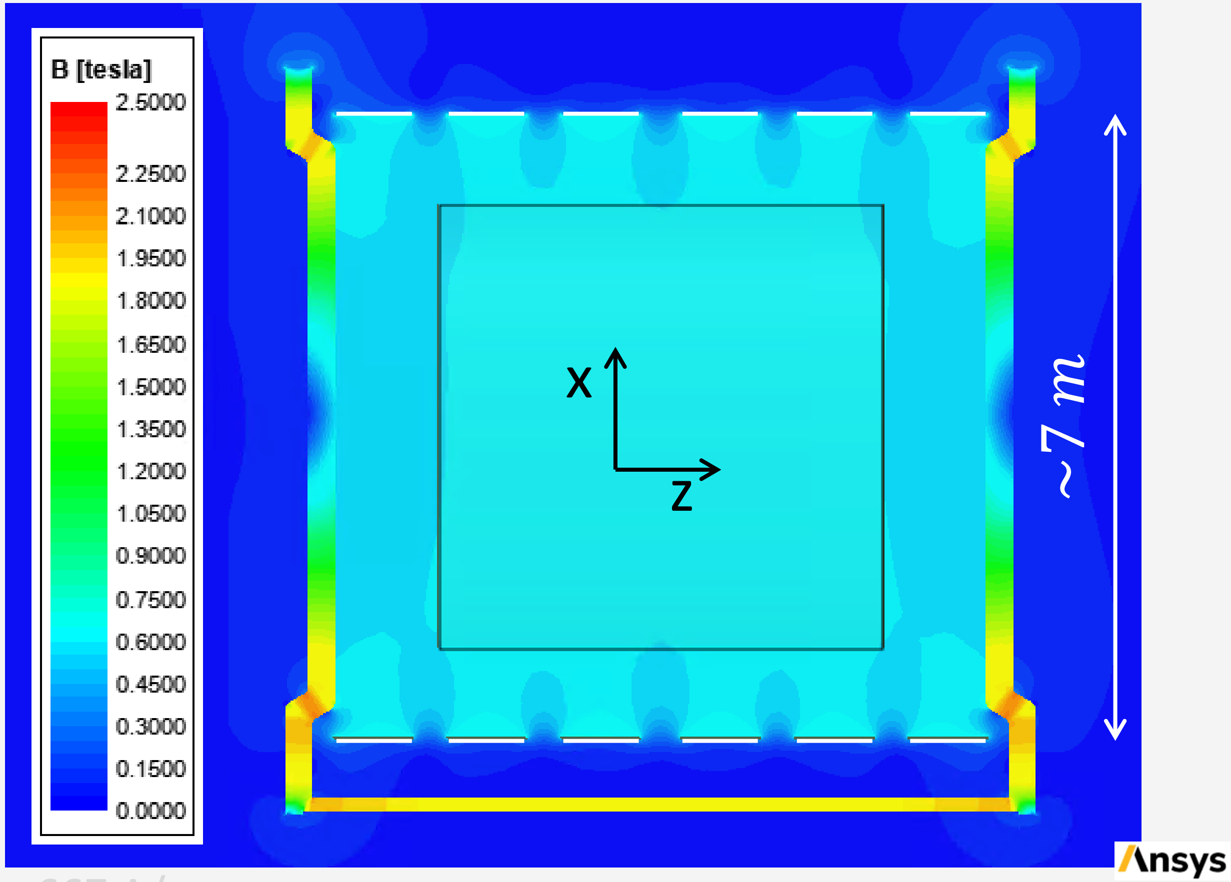
B_{peak} = 0.9 T

I = 4585 A

L = 3.1 H

E = 32.5 MJ

$l_{cond} \approx 16$ km



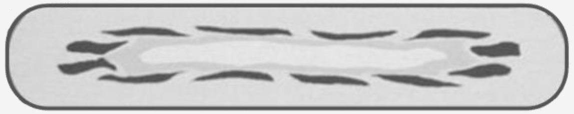
667 A/mm

Wire 1
∅ 1 mm

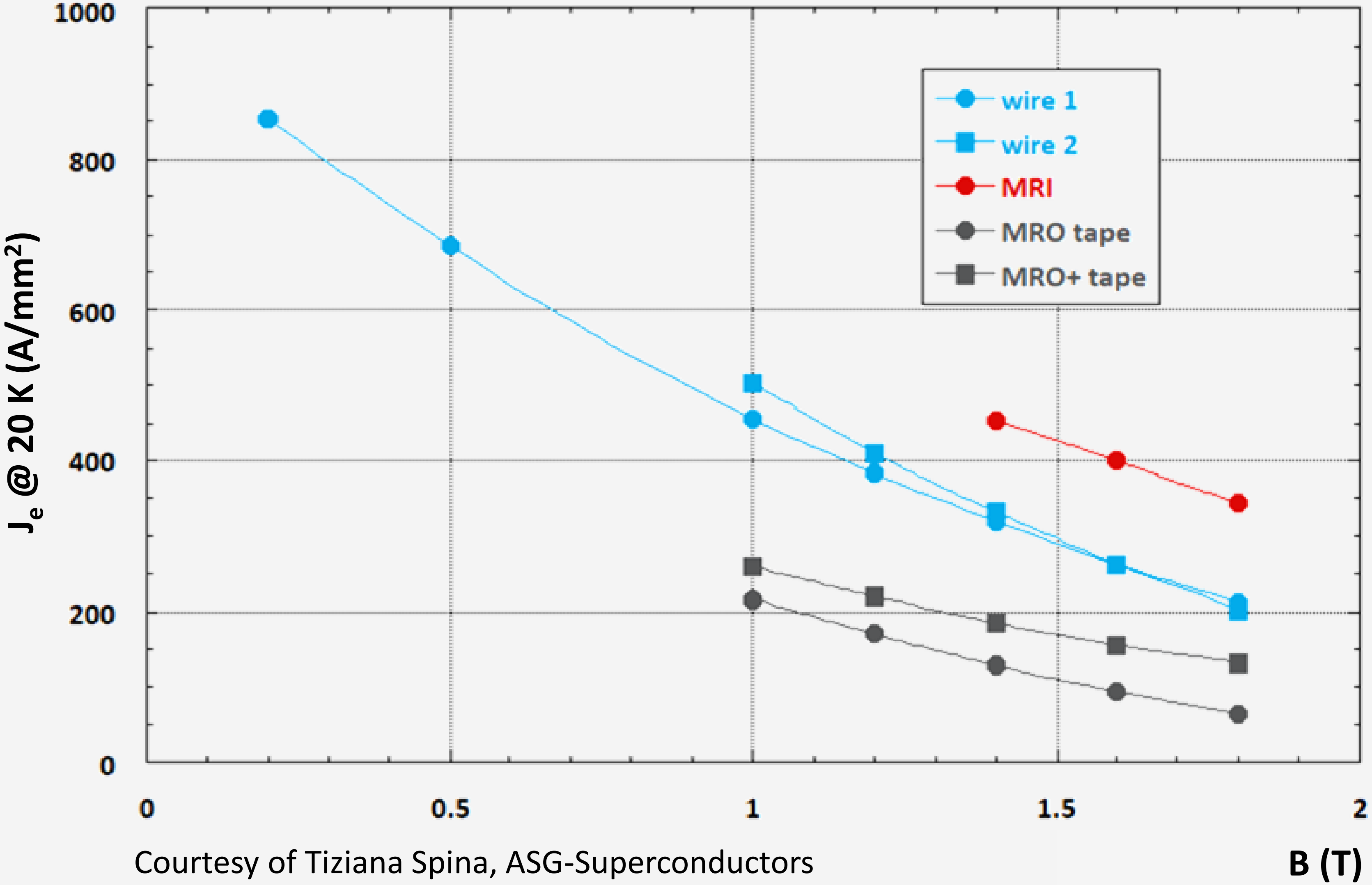
Wire 2
∅ 1.33 mm

MRI
∅ 1.53 mm

MRO/MRO+
3.67 X 0.65 mm



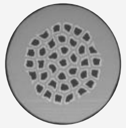
Ex-situ MgB_2 conductors (non-doped)



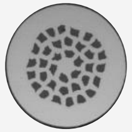
Courtesy of Tiziana Spina, ASG-Superconductors

Ex-situ MgB_2 conductors (non doped)

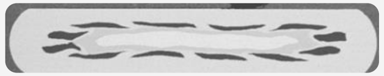
Wire 1



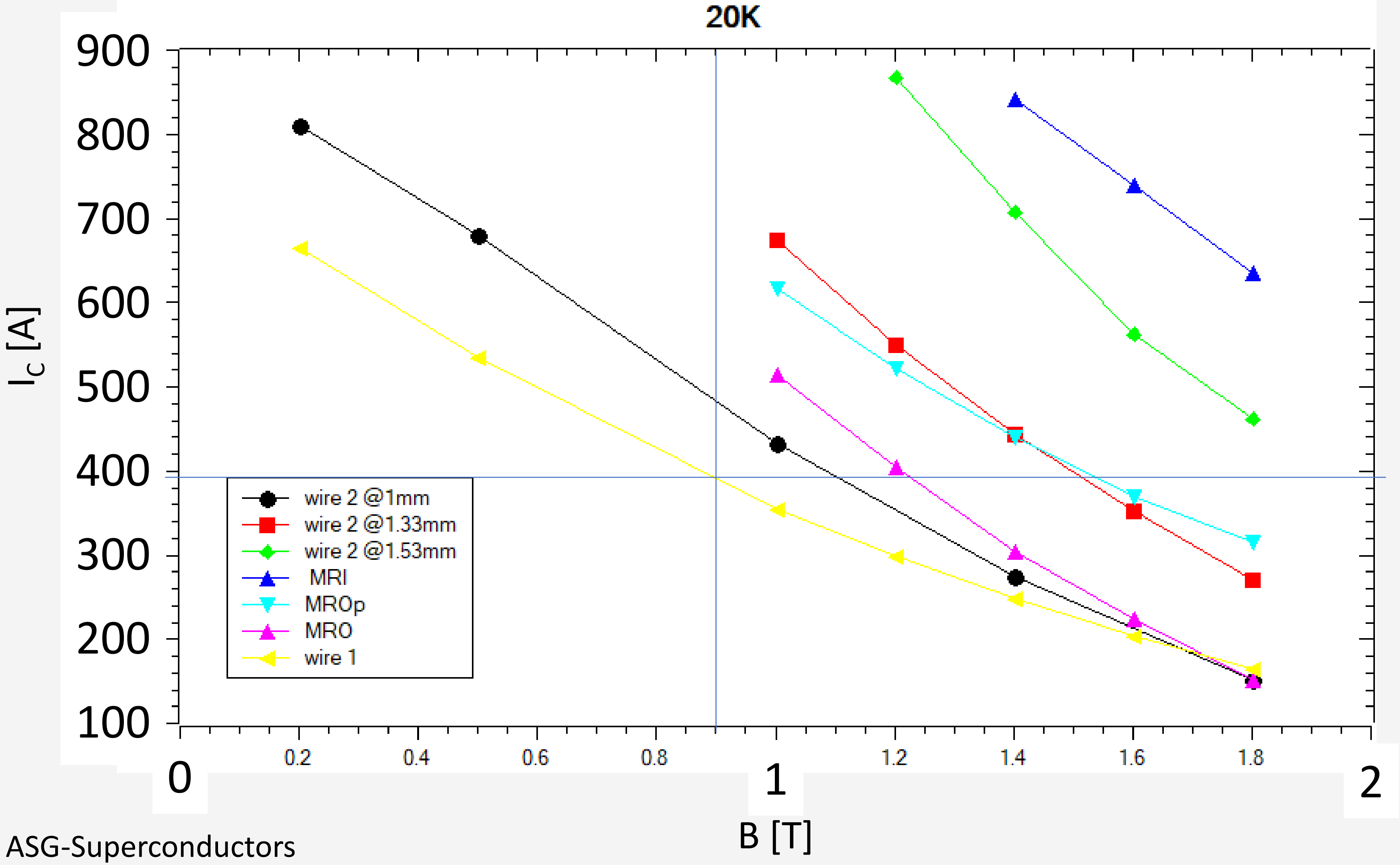
Wire 2



MRO/MRO+



MRI (1,53 mm)



Courtesy of Tiziana Spina, ASG-Superconductors

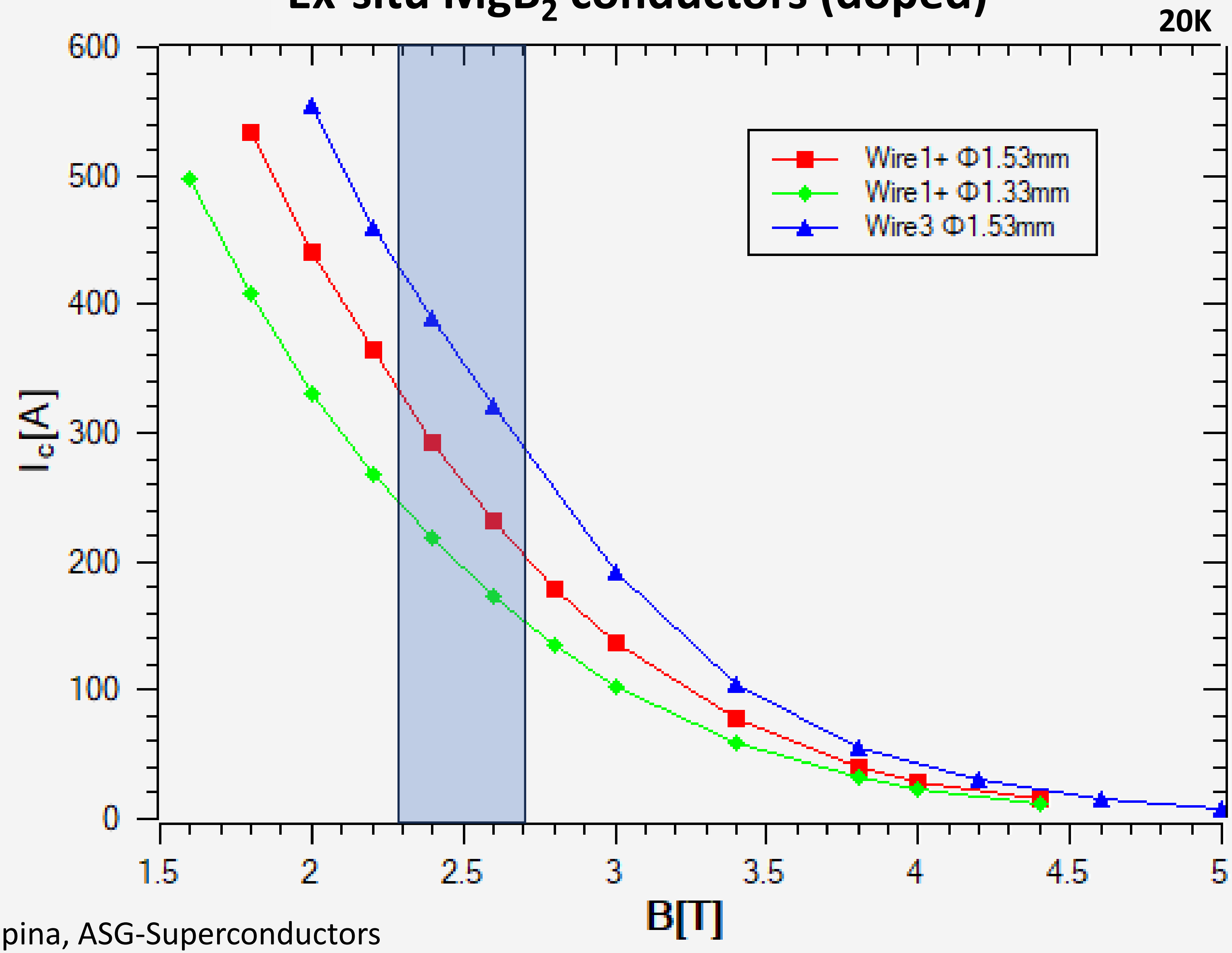
IDEA

Large dimensions

B_{center} up to 2 T → <u>doped MgB_2 conductor</u>

ASG SUPERCONDUCTORS

Ex-situ MgB_2 conductors (doped)



Courtesy of Tiziana Spina, ASG-Superconductors

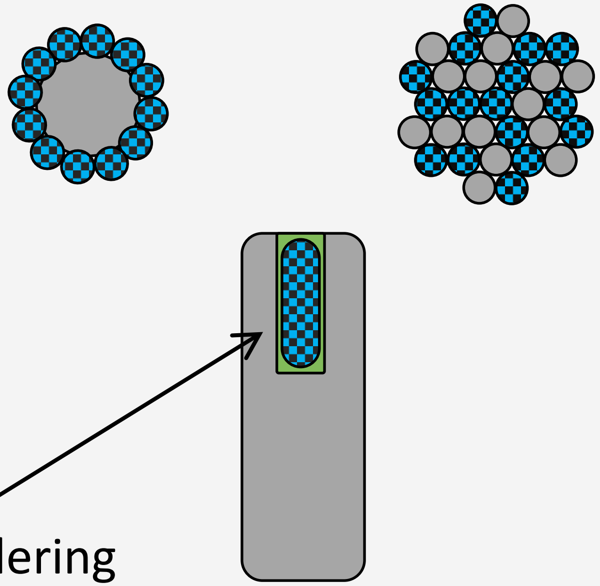
In MgB_2 magnets stability is due to the high specific heat

Aluminium in parallel is for protection:

- Good bonding between cable and aluminium is not necessary (no co-extrusion)
- High purity aluminium is not necessary

It is possible to use conductors obtained:

- by cabling MgB_2 wires and aluminium wires
- by soft soldering MgB_2 in aluminium channels



A remarkable example of MgB_2 wire cabling: **LHC superconducting links**

A. Ballarino, Supercond. Sci. Technol. 27 (2014) 044024

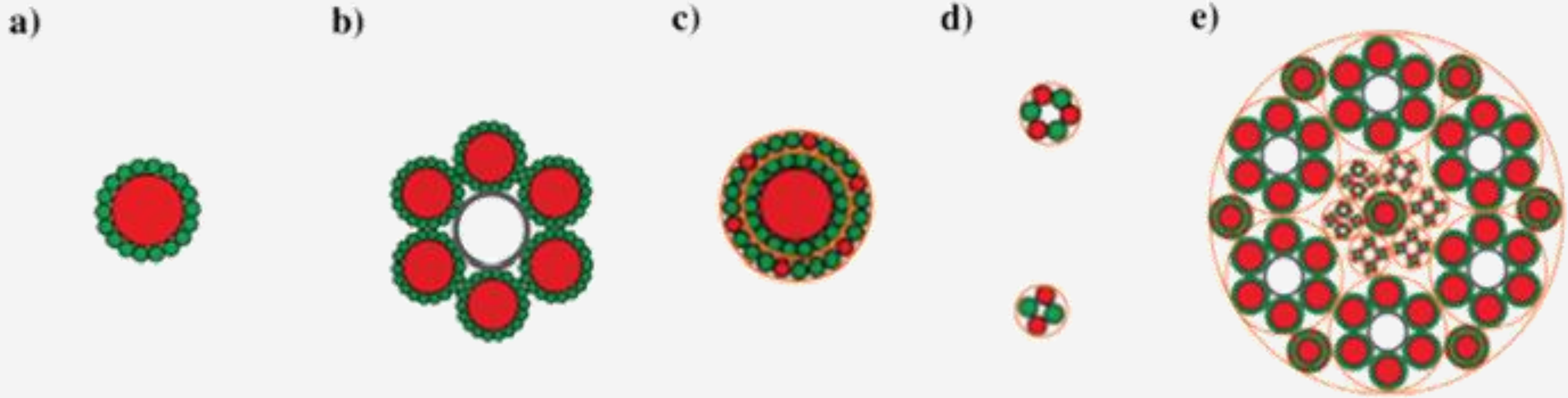


Figure 5. Cables made with MgB_2 round wire. (a) Sub-unit of 20 kA cable, Φ ~ 6.5 mm ; (b) 20 kA cable, Φ ~ 19.5 mm; (c) concentric 2×3 kA cable, Φ ~ 8.5 mm; (d) 0.4 kA cable (top) and 0.12 kA cable (bottom), Φ < 3 mm ; (e) 165 kA cable assembly for LHC P1 and P5 (6×20 kA, 7×2×3 kA, 4×0.4 kA, 18×0.12 kA), Φ ~ 65 mm.

Summary

MgB$_2$ could be an **excellent candidate** to replace NbTi in detector magnets

Detector magnets wound with MgB$_2$ conductors can operate at $T > 10K$, possibly up to $20\ K$.

Consequences of higher operative temperature are:

- higher stability (aluminium is required for protection, not as stabiliser)
- higher thermal conductivity (better indirect cooling)
- higher refrigerator COP

R&D is necessary to develop suitable conductors.

Detector magnet design should be rethought based on MgB$_2$ conductor features (as an example, the quench issue of MgB$_2$ detector magnets could be faced via controlled insulation technique)

THANK YOU FOR YOUR KIND ATTENTION