65th ICFA Advanced Beam Dynamics Workshop
on High Luminosity Circular e+e- Colliders
eeFACT2022

INFN
Istituto Nazionale di Fisica Nucleare

Frascati – 13 September 2022

MGB$_2$ CONDUCTORS FOR FUTURE DETECTOR MAGNETS

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SUPERCONDUCTING DETECTOR MAGNET WORKSHOP

Sep 12 – 14, 2022
CERN
Europe/Zurich timezone

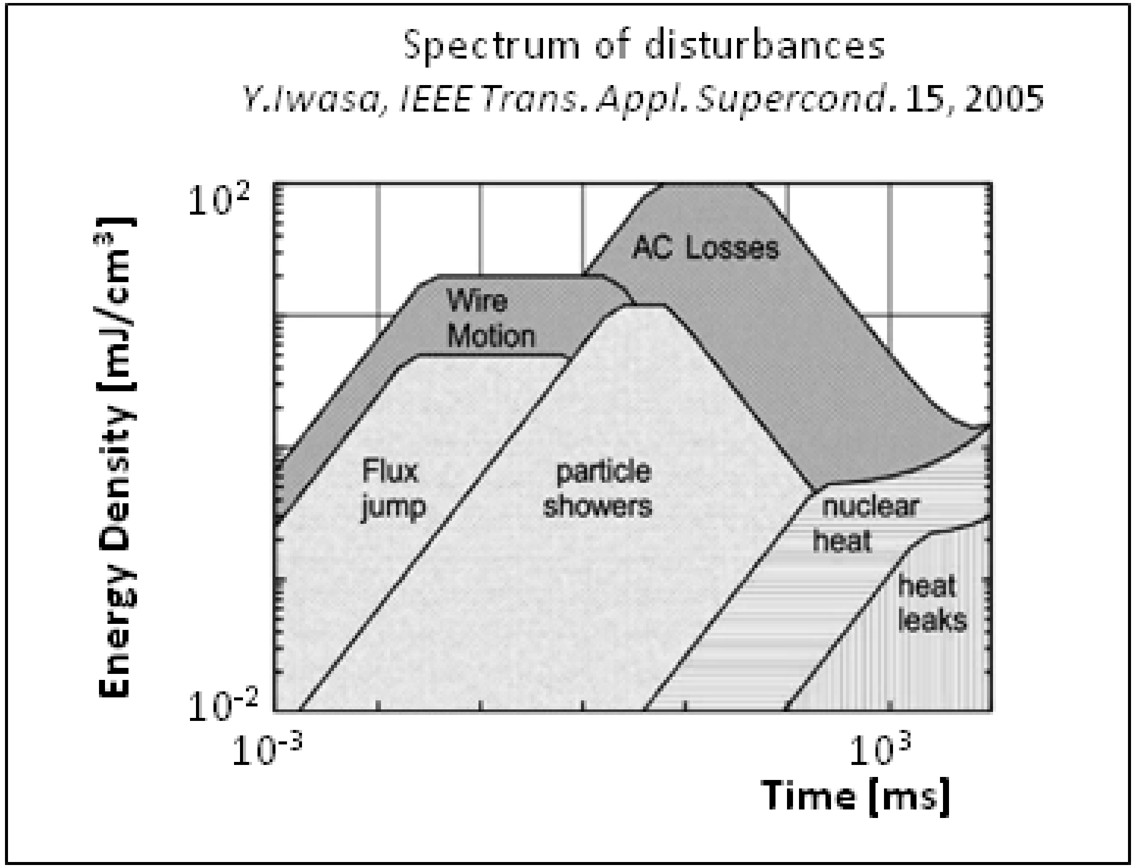
SUPERCONDUCTING MAGNETS FOR PARTICLE DETECTORS

Main characteristics:

- Large volume
- Moderate magnetic field (0.5 to 4 T)
- Transparency to particles is often required
- Generally solenoidal or toroidal shape

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

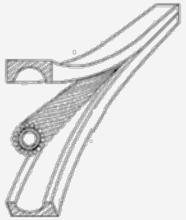
disturbances

cooling power

Cryogenic stability

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

- reduce ρ_{cond}: low resistivity normal metal matrix (in parallel with superconductors)
- reduce J: increase conductor cross section
- Increase h: → magnets in liquid Helium pool
  → forced flow magnets


OMEGA magnet (CERN)

Adiabatic stability

The heat generation terms $(\rho_{cond}J^2$ e $g)$ integrated over time duration 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)

$T_{max} - T_{op}$ is the temperature margin. Typical value for NbTi is between $2\ K$ and $3\ K$

Thin solenoids

Thin solenoids are based on adiabatic stability (indirect cooling)

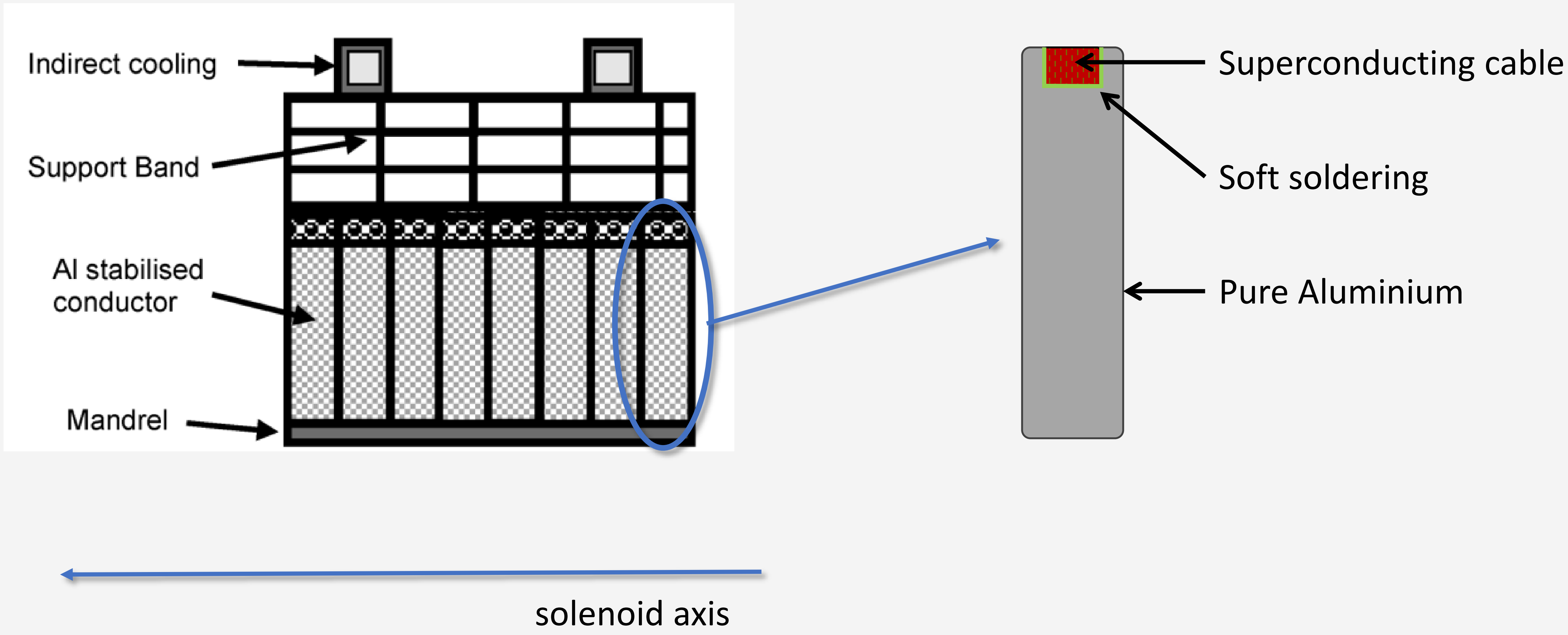
Aluminum: Low density, high radiation length, low resistivity at 4.2 K (RRR>2000)

Pure Aluminum 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
- allows positioning calorimeters outside the magnet.

The first detector solenoid based on aluminum stabilized conductor was CELLO (DESY) in 1978

Sketch of the CELLO magnet



Superconducting cable

Soft soldering

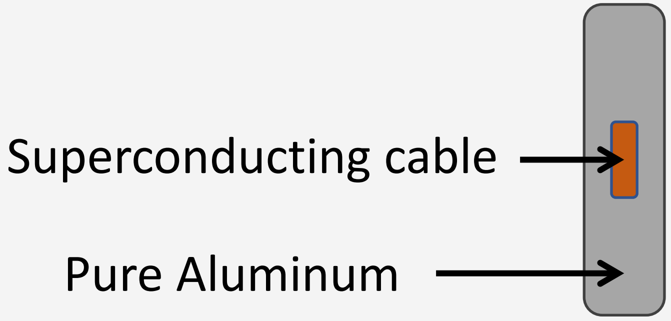
Pure Aluminium

solenoid axis

Thin solenoids

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

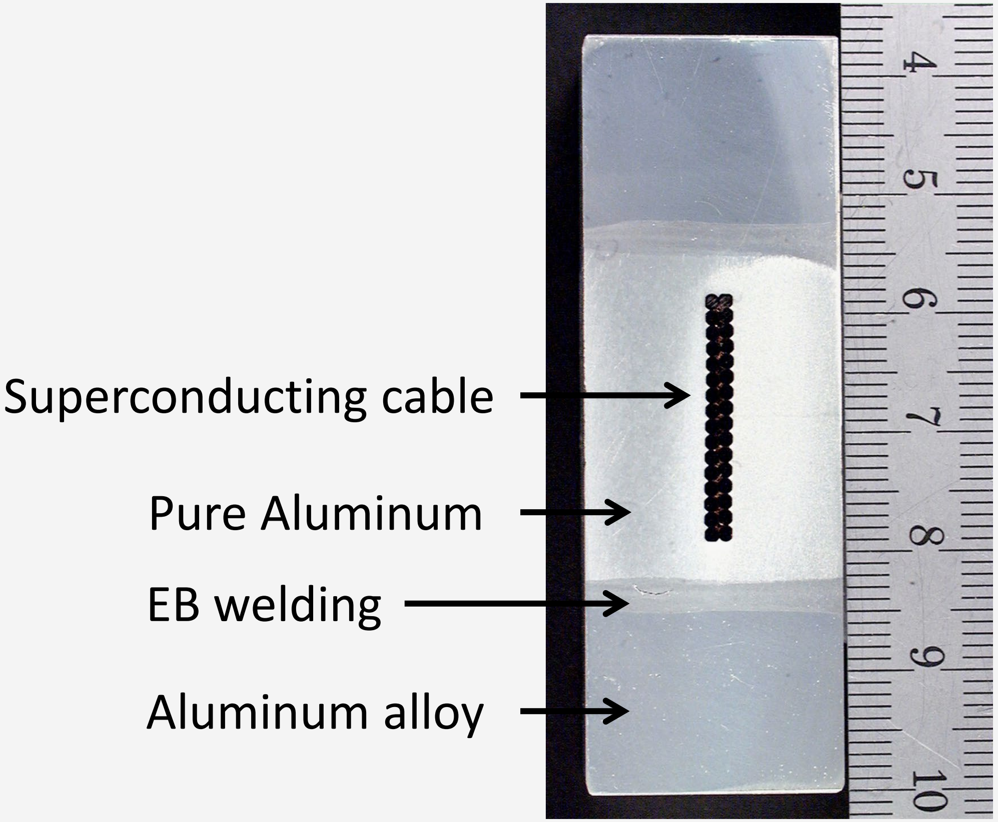
The co-extrusion technology was applied for the first time in the CDF magnet (FERMILAB) in 1984



Thin solenoids

CMS conductor

Aluminum stabilized cable reinforced with EBW Aluminum alloy

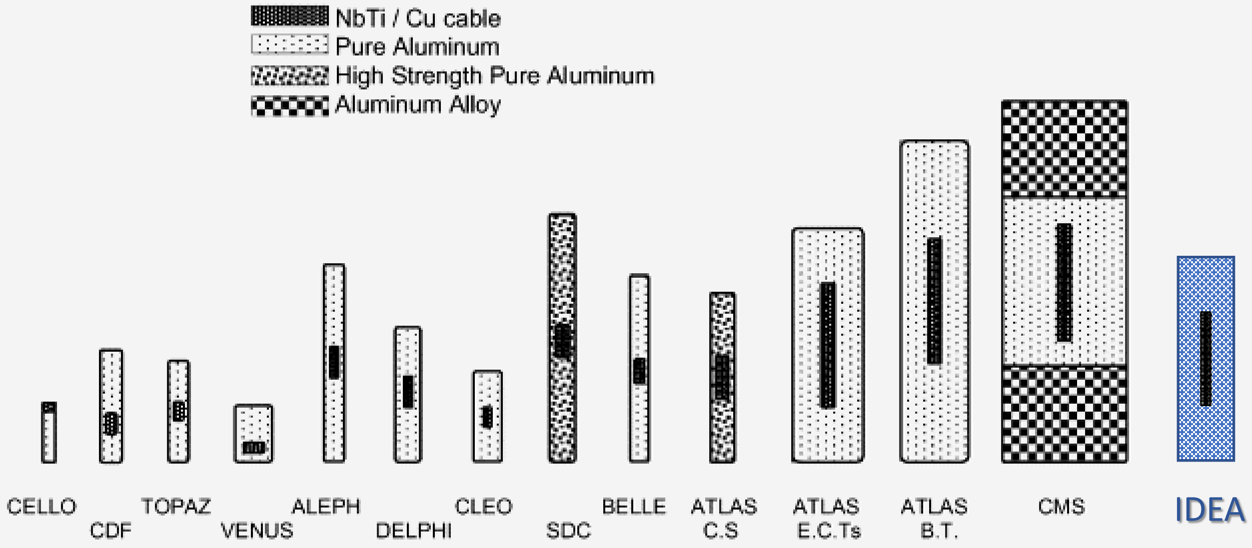


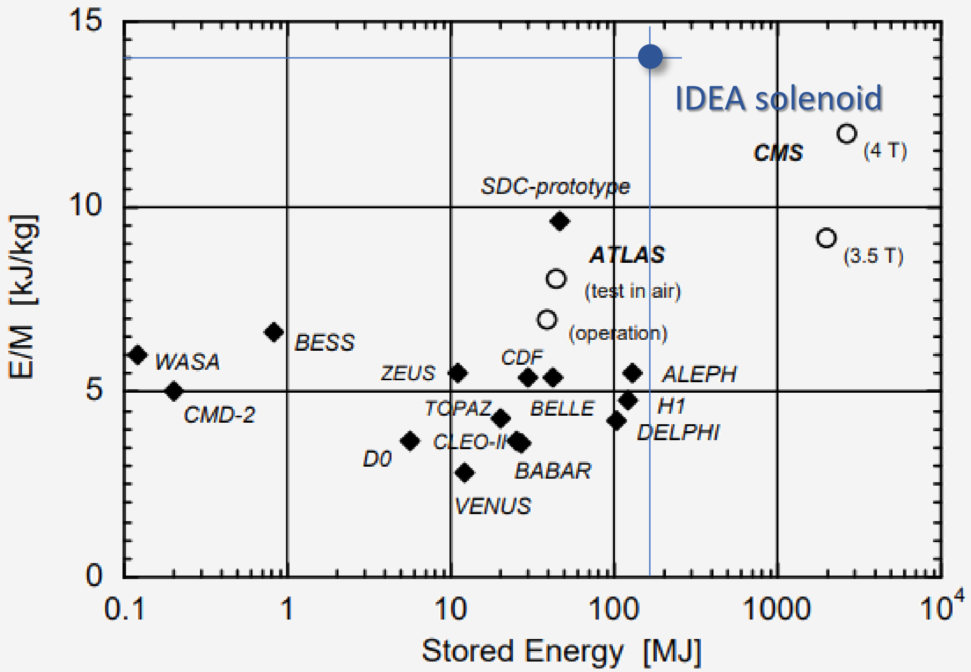
Thin solenoids

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

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

Thin solenoids evolution





A.Yamamoto and Y.Makida, *Nuclear Instruments and Methods in Physics Research* A 494 (2002)

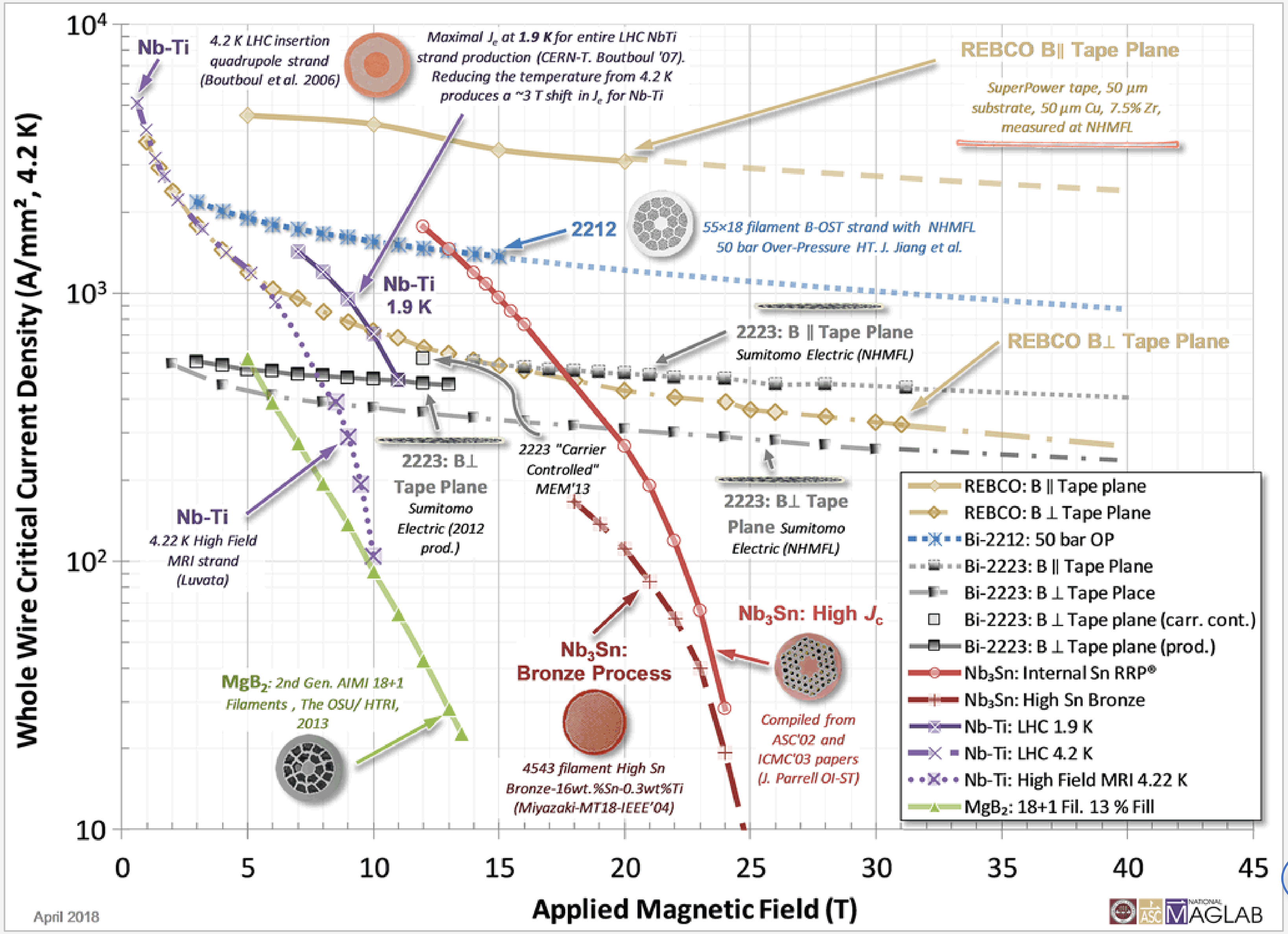
IDEA data from N.Deelen *https://indico.cern.ch/event/1162992/contributions/4945512/* presented @ *Superconducting magnet Workshop*, Sept. 12th 2022

At present, only NbTi alloy is used for detector magnets.

NbTi is ductile, relatively cheap and robust (J_C is not affected by mechanical stress).

However, fabrication of aluminum stabilized conductors is an industrial process performed by very few firms.

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	$T_c = 38\ K$

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

It is produced by reacting the precursors (Mg and B) powders at about 700°C for few minutes

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 $J_c = 0$)
(@ B_{irr} superconductivity is hold, but no current can flow)

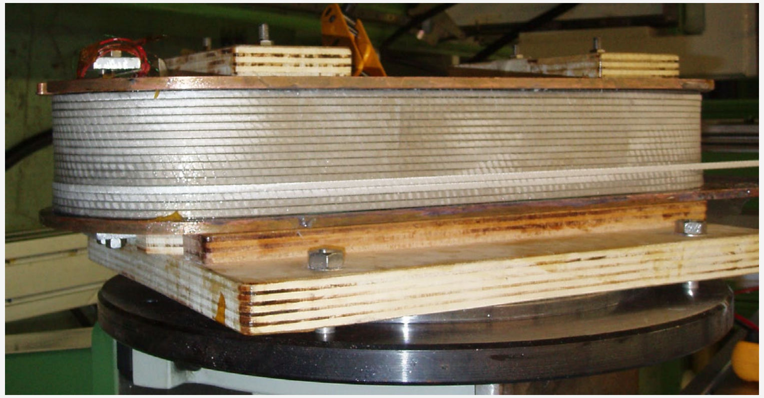
Pure MgB_2: $B_{irr} \approx 12\ T$
Doping increases B_{irr}

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 4 cm for a 0.65 mm thick tape).

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 $T > 10\ K$ $(T_c = 38\ K)$

More efficient cryogenics

Higher COP

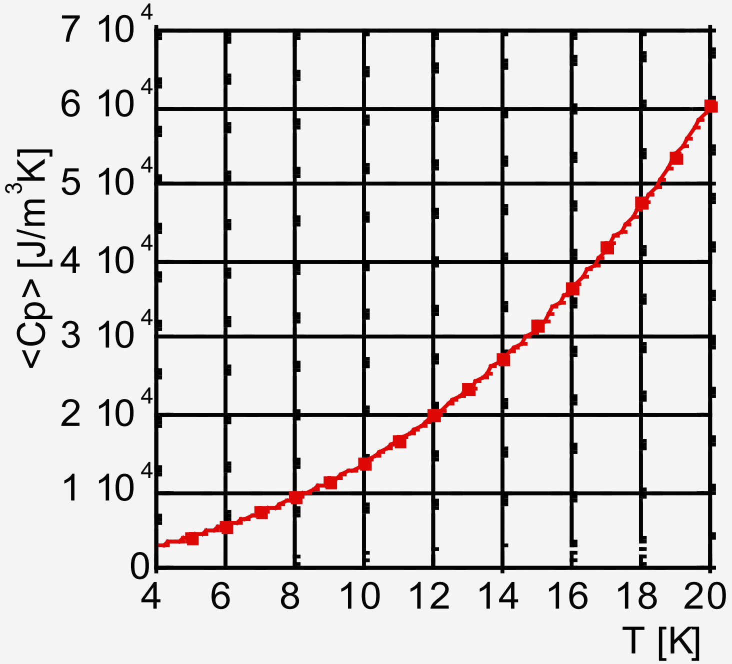
Better conduction cooling

$$\frac{K_{Al6061}@12\ K}{K_{Al6061}@4.2\ K} \approx 3$$

Higher energy density margin

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

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



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

First proposals about MgB_2 conductors coupled with Aluminum 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

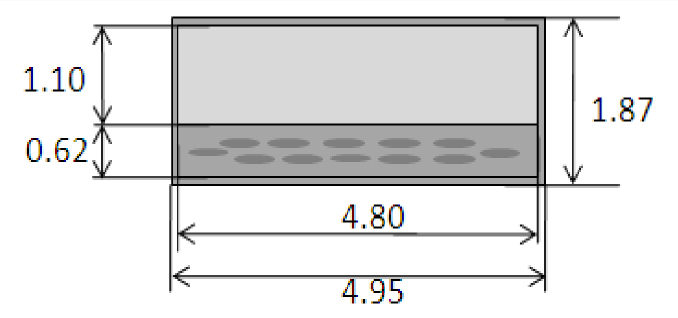
R. Battiston, W. J. Burger, V. Calvelli, V. I. Datskov, S. Farinon, and R. Musenich
Superconducting Magnets for Astroparticle Shielding in Interplanetary Manned Missions
IEEE Trans. on Appl. Supercond., 23 (3), 2013, 4101604

SR2S Space Radiation Superconducting Shield

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

Conductor: Titanium clad MgB$_2$ tape + Aluminum 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 SR2S conductor prototype

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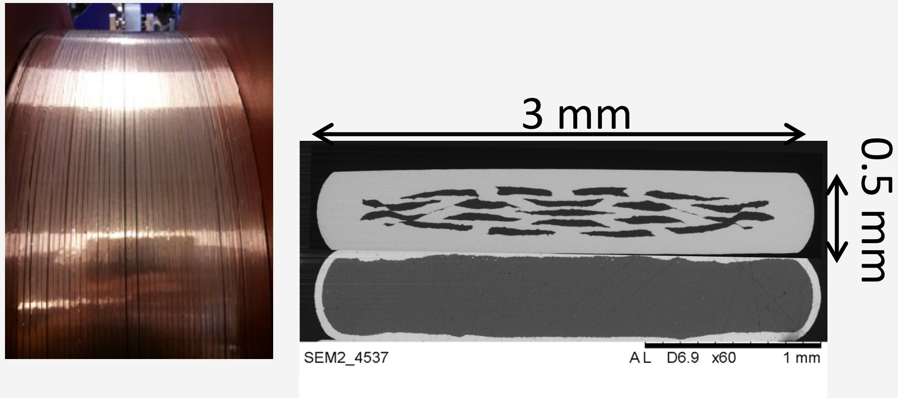
Columbus Superconductors [now ASG SUPERCONDUCTORS]

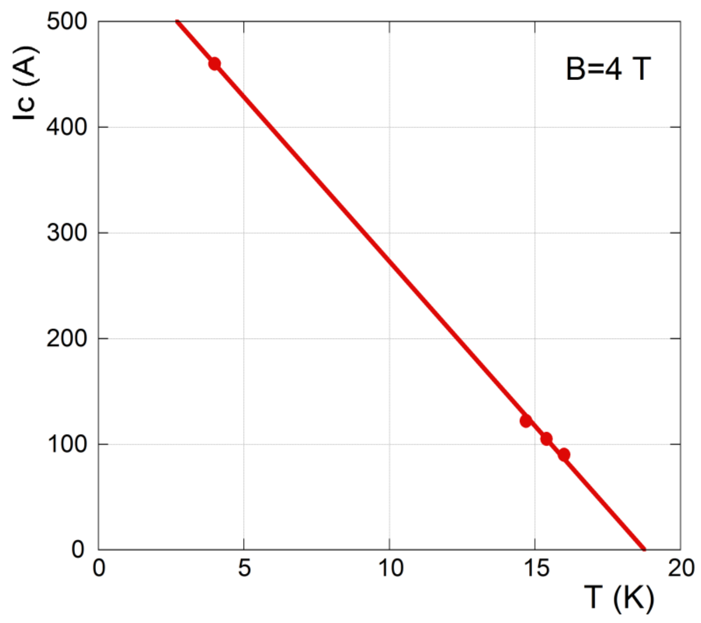

360 m Ti-MgB_2


Ti-MgB_2 tape during copper plating


copper plated Ti-MgB_2 tape



Cu-Ti-MgB_2 tape

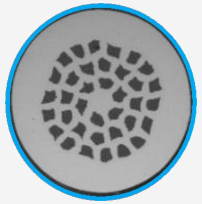


Problems occurred during aluminum tape soldering due to different thermal contractions.
Due to tight schedule and limited funds, no further attempts were made to solder the aluminum tape.

Present status of ex-situ MgB$_2$ conductors

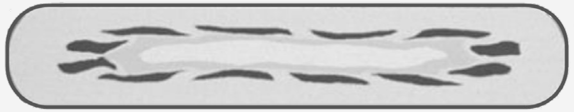
Wire 1

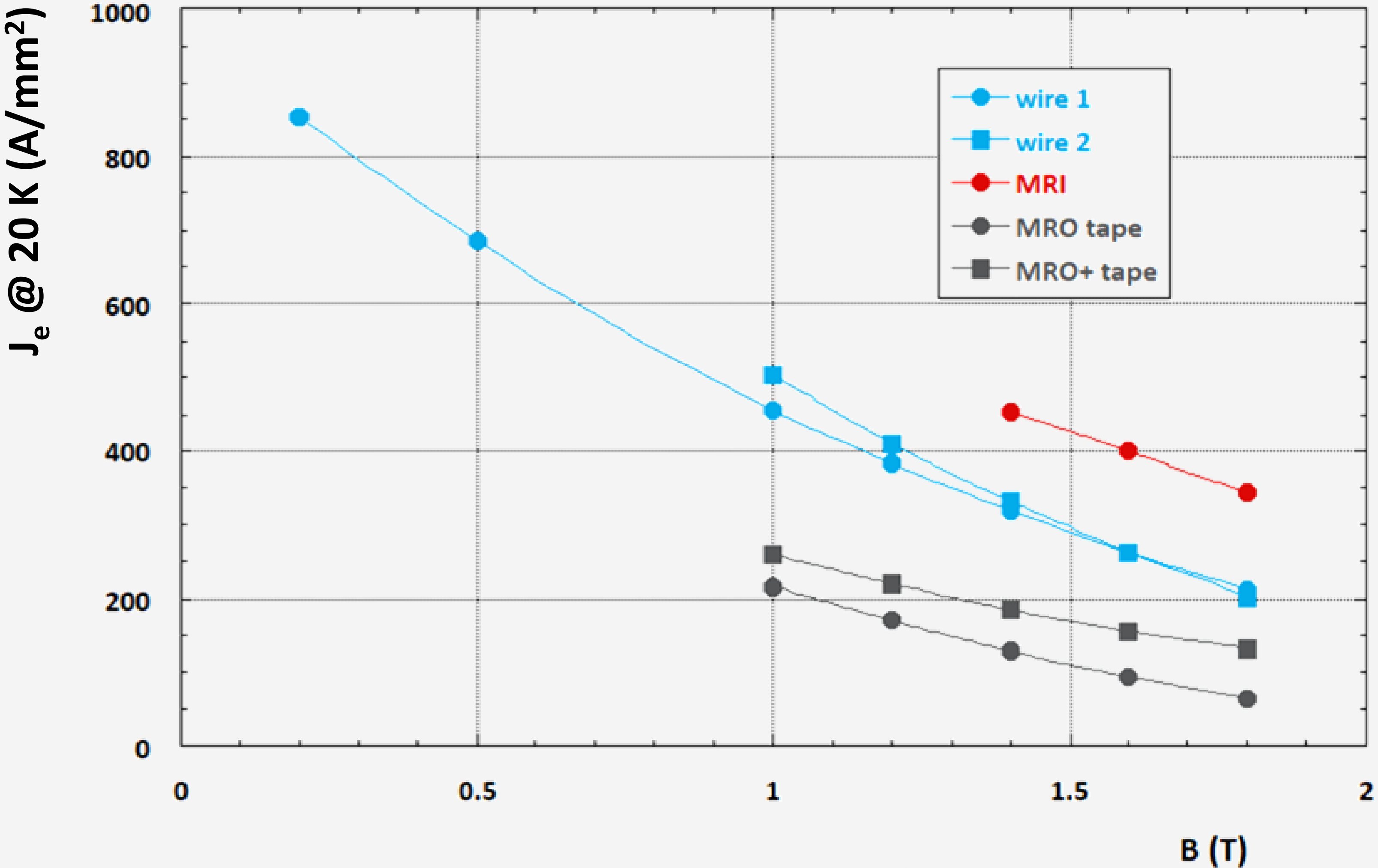
Wire 2



MRI

MRO/MRO+





$$J_e(15K, 2T) \approx 400 - 600\ {}^{A}/_{mm^2}$$

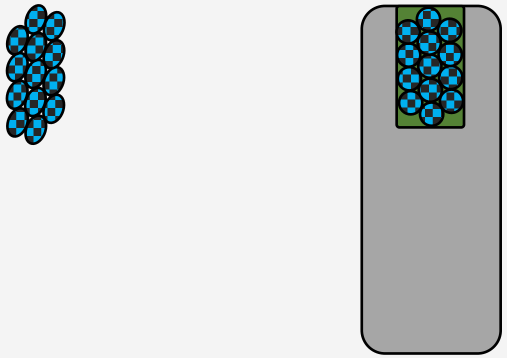
Courtesy of Tiziana Spina, ASG-Superconductors

In MgB$_2$ magnets operating at $T > 10\ K$ stability is due to the high specific heat

Close contact between the superconducting composite and aluminum is not necessary

- In principle, it is possible to use conductors obtained by cabling MgB2 wires and aluminum wires

- Limited deformation is possible before heat treatment to obtain an almost flat cable



- MgB2 detector magnets could be protected via controlled insulation technique

A remarkable example of cabling of MgB2 wires: the LHC superconducting links

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

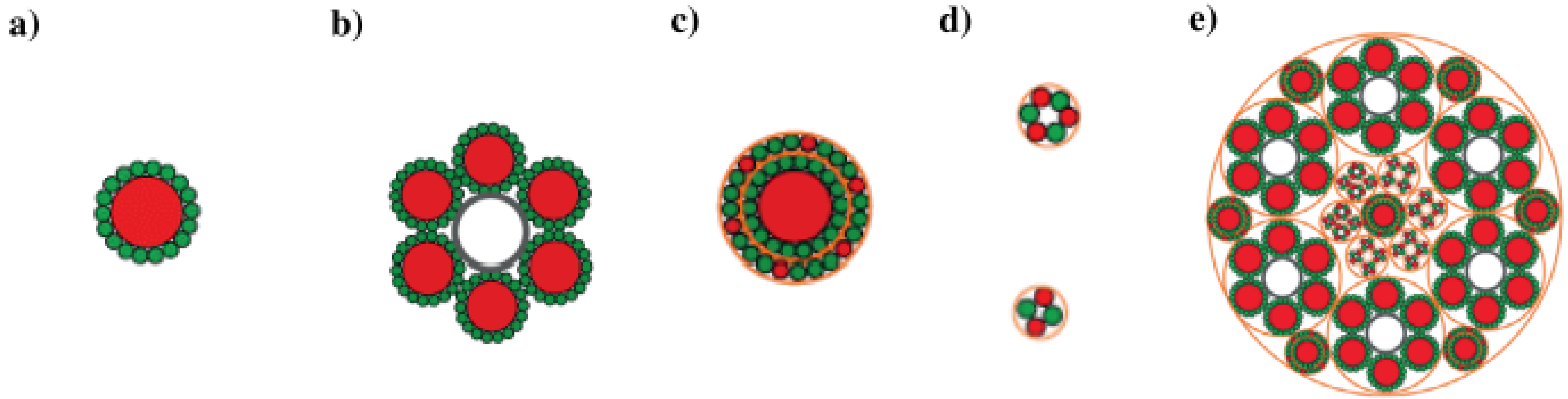


Figure 5. Cables made with MgB_2 round wire. (a) Sub-unit of 20 kA cable, $\Phi \sim 6.5$ mm ; (b) 20 kA cable, $\Phi \sim 19.5$ mm; (c) concentric 2×3 kA cable, $\Phi \sim 8.5$ mm; (d) 0.4 kA cable (top) and 0.12 kA cable (bottom), $\Phi < 3$ mm ; (e) 165 kA cable assembly for LHC P1 and P5 (6×20 kA,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

Conclusions

- Detector magnets based on MgB2 conductors can be operated at T>10 K
- Consequences of higher operative temperature are:
  - higher stability
  - higher thermal conductivity (better indirect cooling)
  - higher refrigerator COP
- R&D is necessary to develop suitable conductors
- Detector magnet design must be rethought based on MgB2 conductor features (as an example, the quench issue of MgB2 detector magnets could be faced via controlled insulation technique)