MgB_2 cables from wires made by PIT and IMD process

P. Kováč, L. Kopera, T. Melišek, J. Kováč, M. Kulich and I. Hušek
Institute of Electrical Engineering of SAS, 841 04 Bratislava Slovakia

Motivation: MgB_2 is a **compound well** formable into **wires** commercially available in **long-lengths** (..km) +

Requirements for applications (e.g. motors/generators):

- **high currents in low fields** region and *T* ~ 20 K (no C-doping)
- **MgB_2 cables offer: (i)** current **up scaling**, **(ii)** lowered **coil diameters,** and **(iii) AC loss** reduction (decoupling) – twisting/cabling

Therefore, properties of mostly *Rutherford* **MgB_2 cables** made of **PIT and IMD** strands were studied

MT25

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Amsterdam
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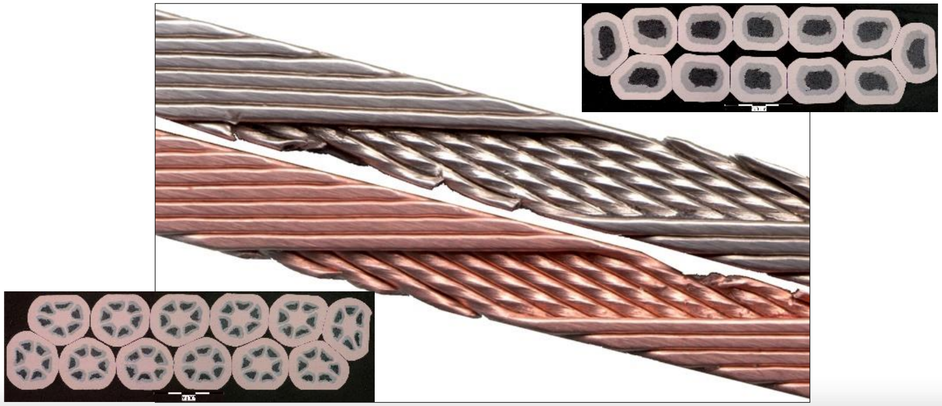
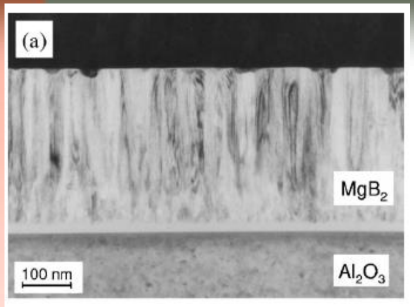
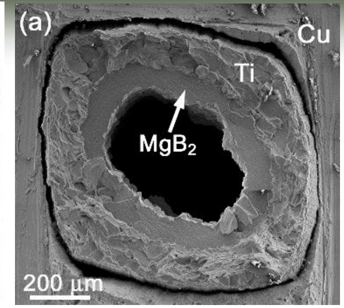


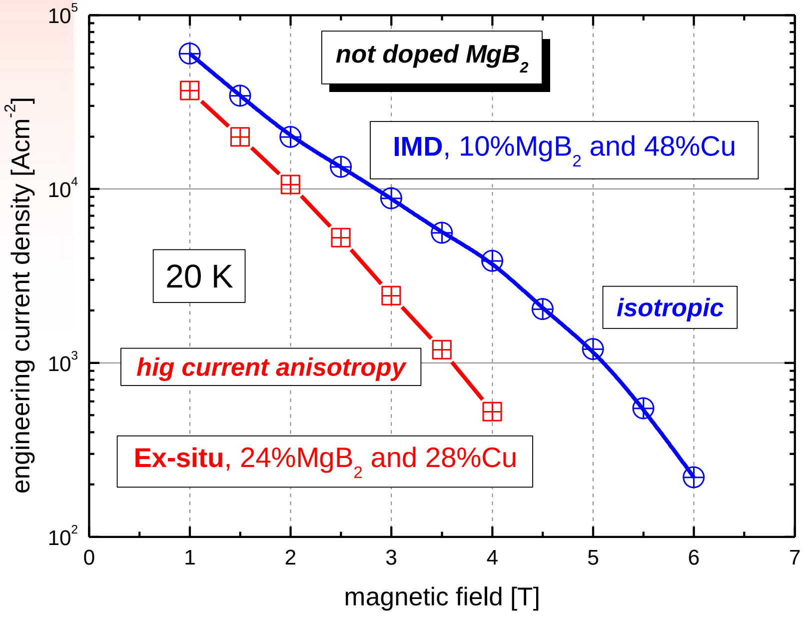
Current densities of PIT and IMD MgB_2 wires



MBE film, ~ 300 nm

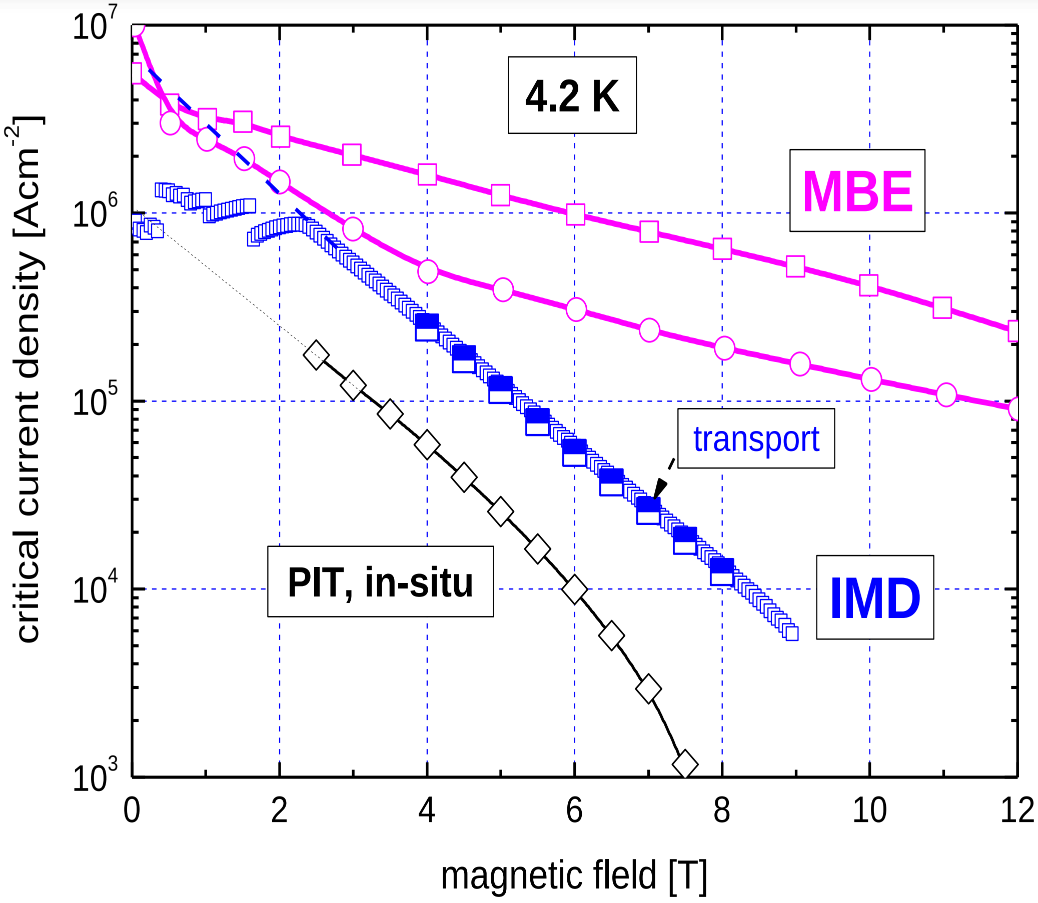


IMD layer, ~ 70 µm



IMD wire with **10% MgB_2 and 48% Cu** has **2 times higher J_e** at 2T in comparison to PIT ex-situ tape with 24% MgB_2 and 28% Cu

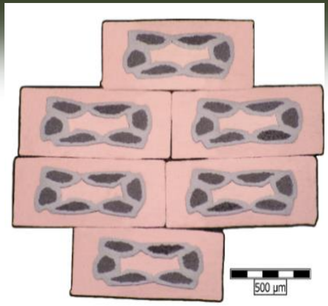
H. Yamamoto et al. *Appl Phys. Lett* **90** (2007) 142516



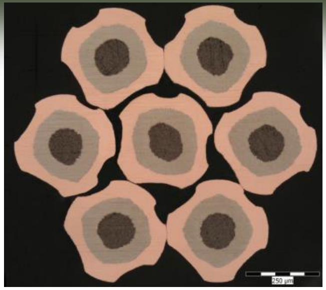
B* < 2 T – comparable *J_c* for MBE and IMD** due to ***dense, ***no porous***, ***low MgO*** content MgB_2 layer

P. Kovac et al., *Sup Sci and Technol* **27** (2014) 065003

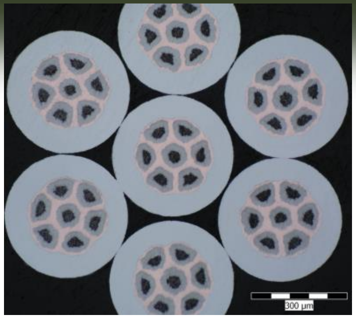
Cables made of round and flat MgB$_2$ strands



MgB$_2$/Ti/GlidCop

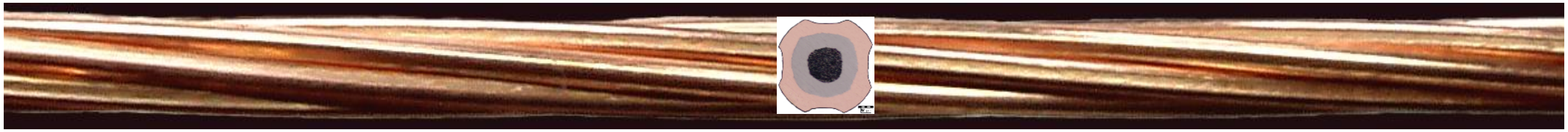


MgB$_2$/Ti/Cu



MgB$_2$/NbTi/Cu/SS

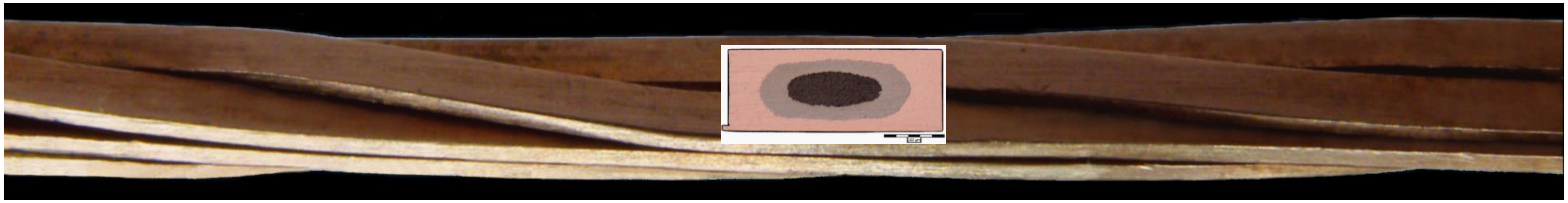
C7



Continually transposed conductor (CTC)

L_t = 15 mm

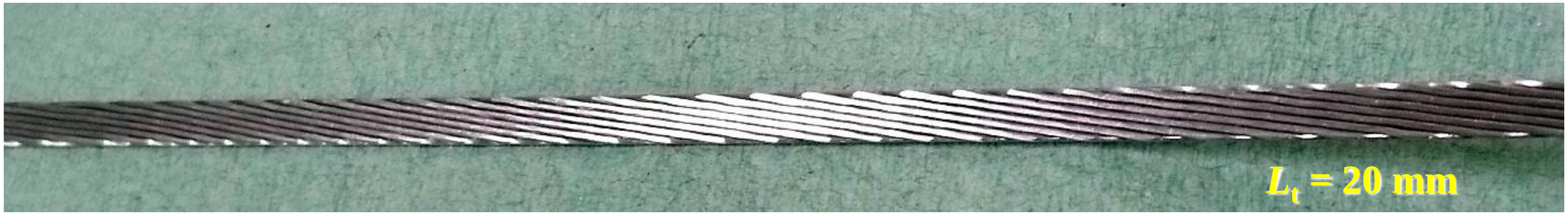
CTC6



Rutherford cable

L_t = 15 mm

R12

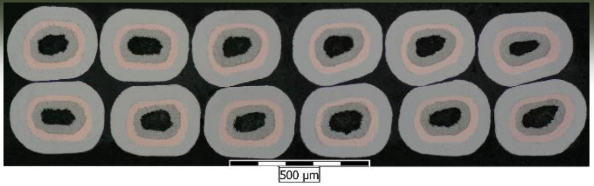


Up to now, **variable MgB$_2$ cables** have been assembled and **no** apparent **degradation of transport currents** occurred due to cabling.

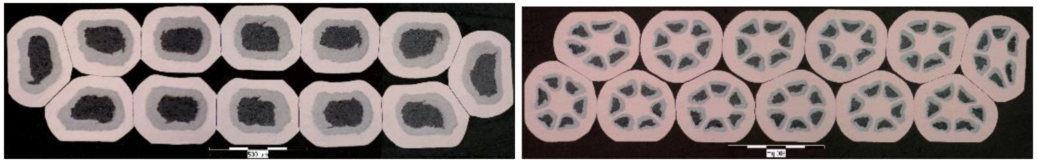
Husek I et al, *Cryogenics* **49** (2009) 366

Kovac P et al. *Sup Sci and Technol* **21** (2008) 125003 /Kopera L et al. *Sup Sci and Technol* **26** (2013) 125007

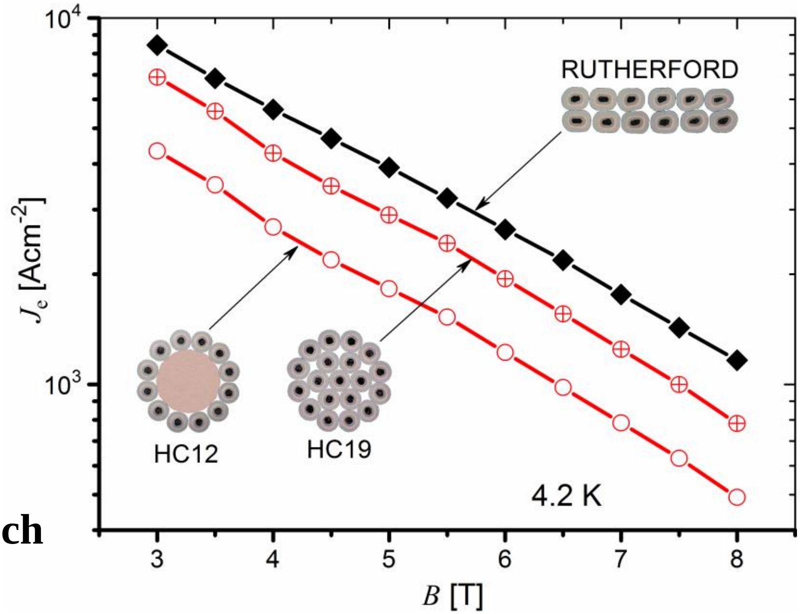
Rutherford MgB_2 cables made of PIT strands



MgB_2/Ti/Cu/Monel wires 0.30 mm, **IEE**
cable **0.54x 2.0mm**



MgB_2/Nb/CuNi and MgB_2/Nb wires 0.39 mm from **Hyper Tech**
cables **0.72x2.55mm**



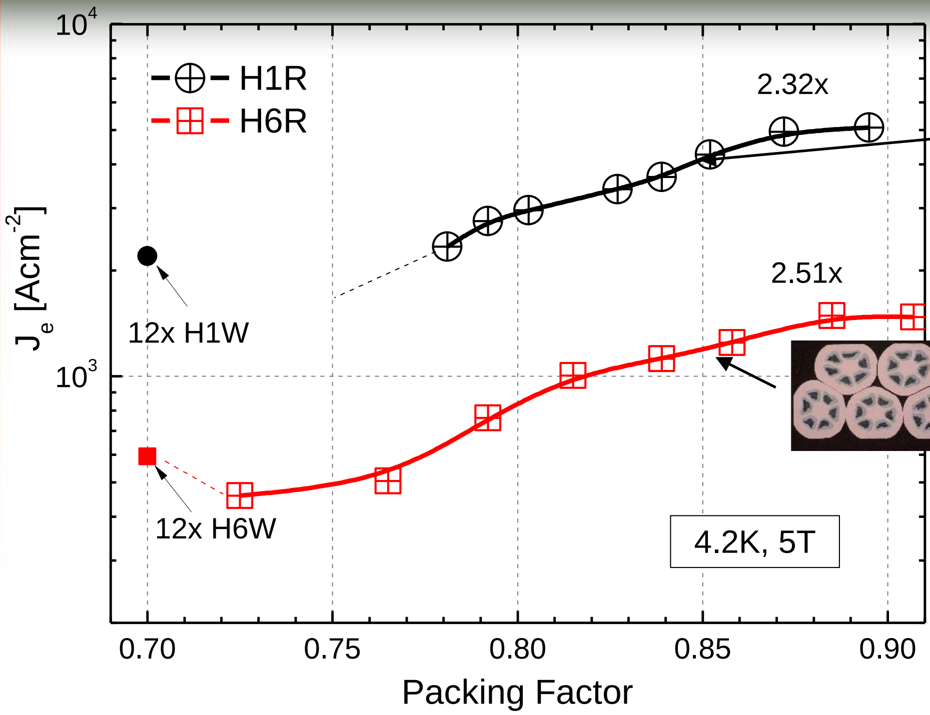
Rutherford cable:

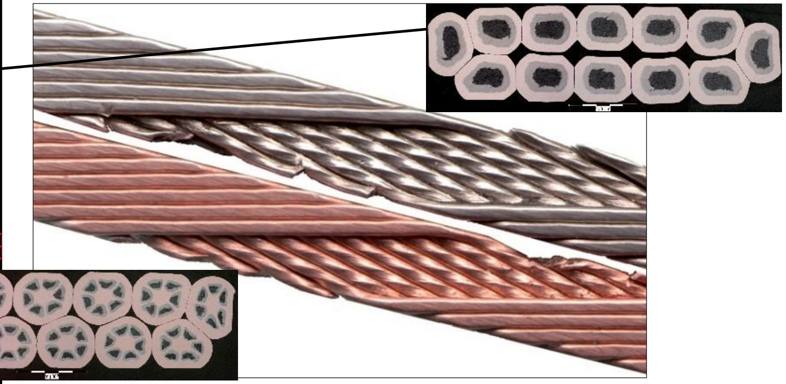
- I_c increased by **densification** of as-drawn wires.
- high packing factor, **no damaging** of wires.
- higher **engineering J_e** than for circular cables.

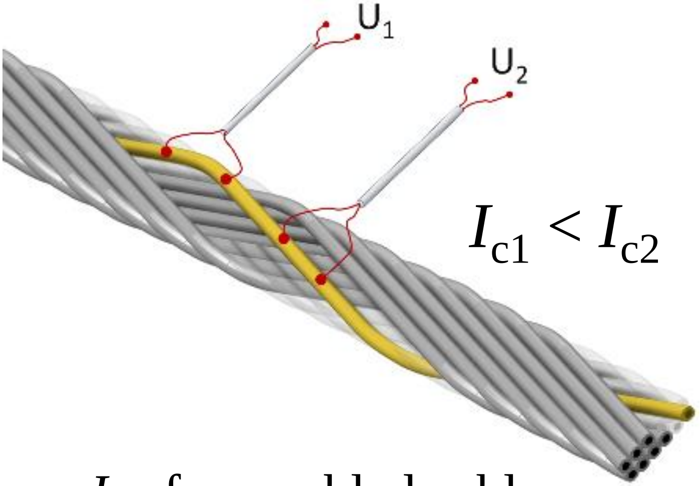
Kopera L et al. *Sup Sci and Technol* **30** (2017) 015002

Densification of Rutherford cables by rolling

Cables made of **HyperTech** strands 0.39mm.







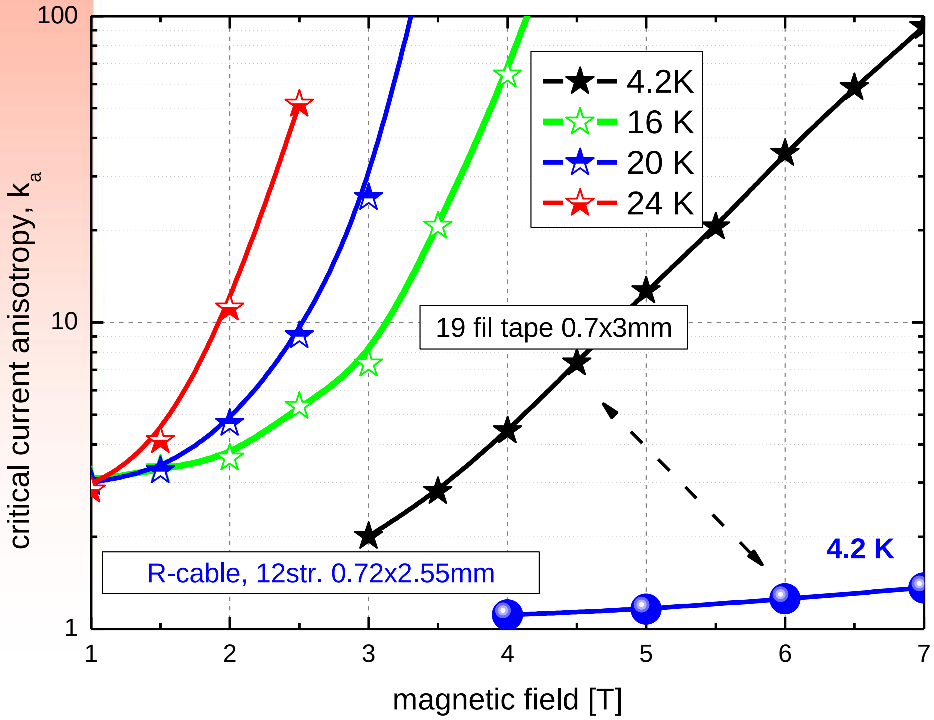
$I_{c1} < I_{c2}$

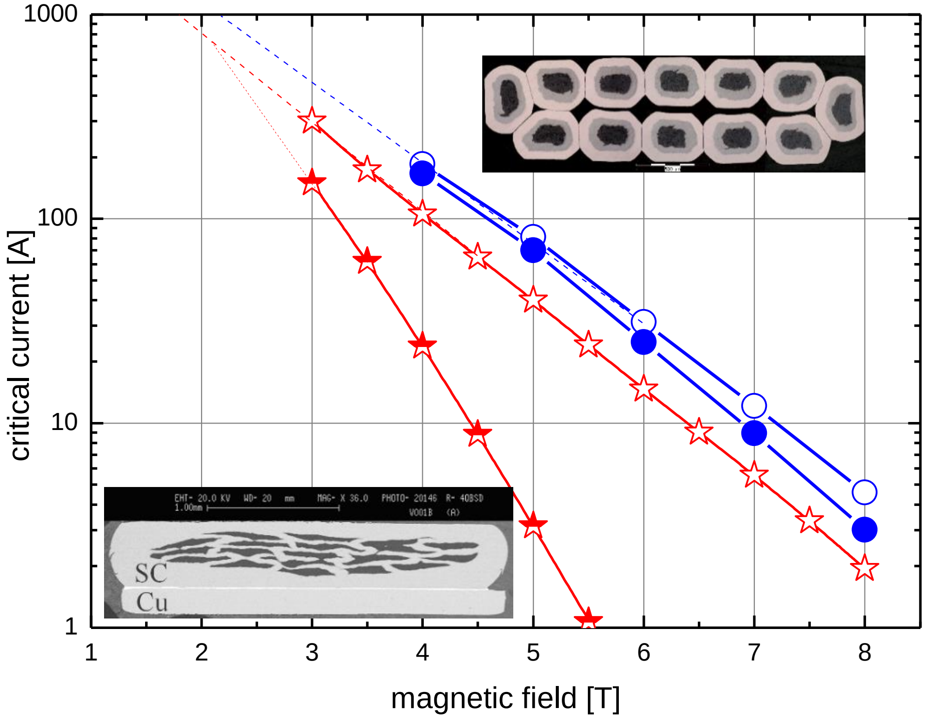
Packing factor of 12 not deformed wires is 0.7.

Low J_c of as-drawn wires (not dense powder) – low J_e of assembled cable. Rolling deformation of R-cable: elimination of void area and powder densification, which increases I_c and allows to doubled J_e of the cable.

Kopera L et al. *Sup Sci and Technol* **30** (2017) 015002

Current anisotropy of R-cable and MgB_2 tape



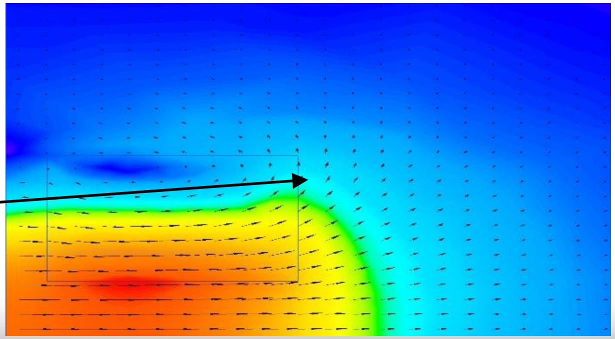


Flat Rutherford cable: - *nearly* ***no I_c anisotropy***

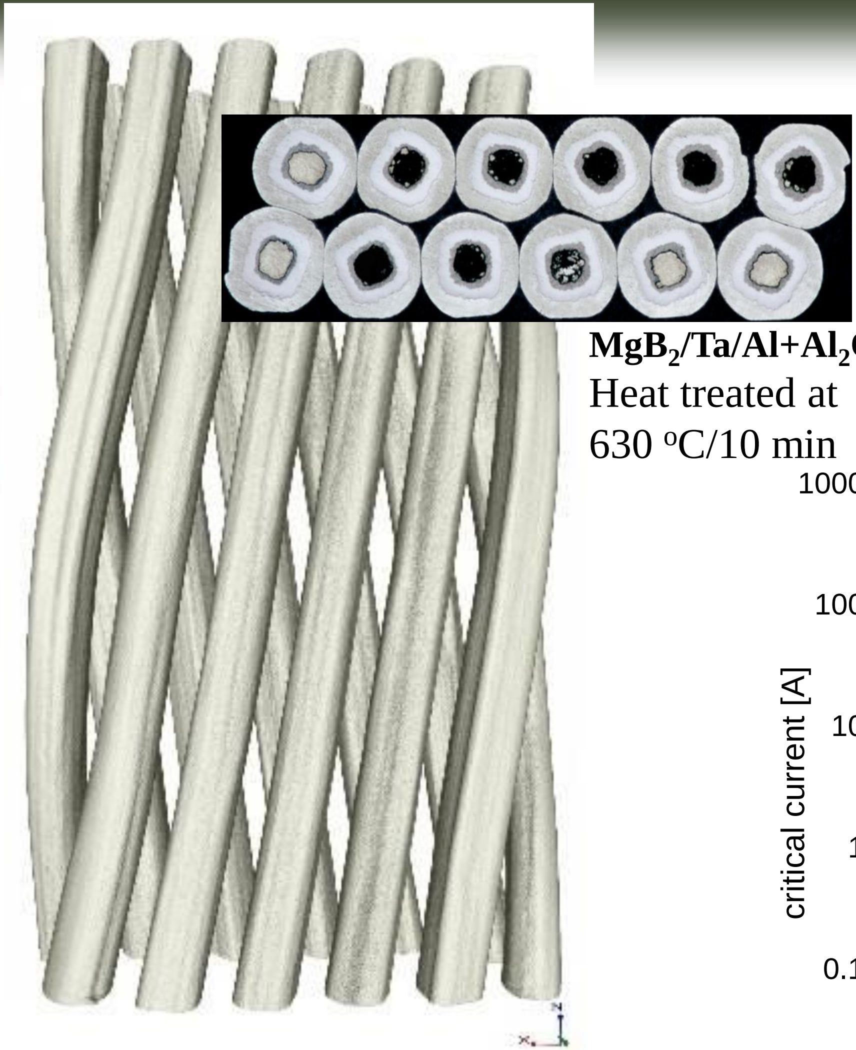
Flat conductor: - ***high anisotropy***:

$k_a = I_{c\text{-par.}} / I_{c\text{-perp.}} = 10$ at 24 K and 2 T

which can ***reduce the total coil's current*** *substantially due to radial field component at the coil's flanges.*

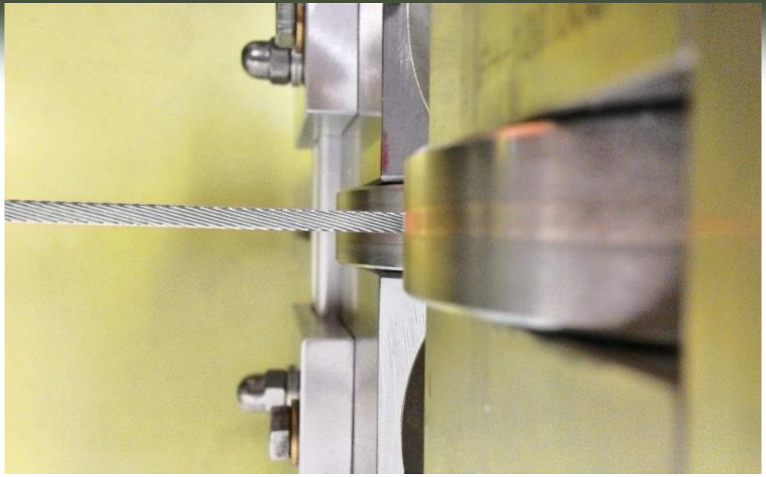


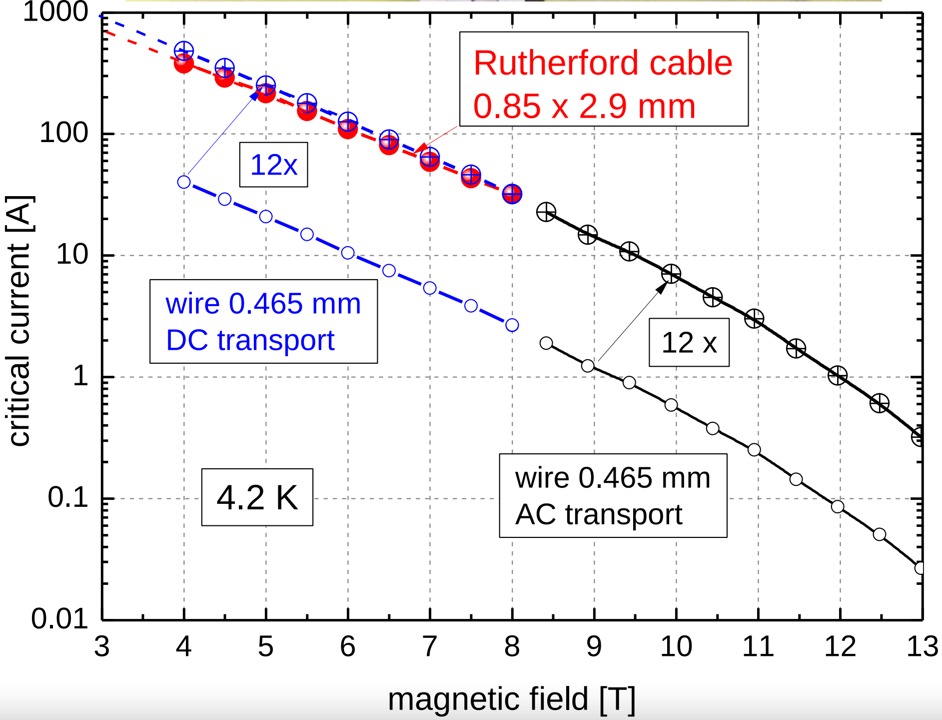
Rutherford MgB_2 cable with IMD/Al+Al_2O_3 strands



MgB_2/Ta/Al+Al_2O_3
Heat treated at
630 ^oC/10 min

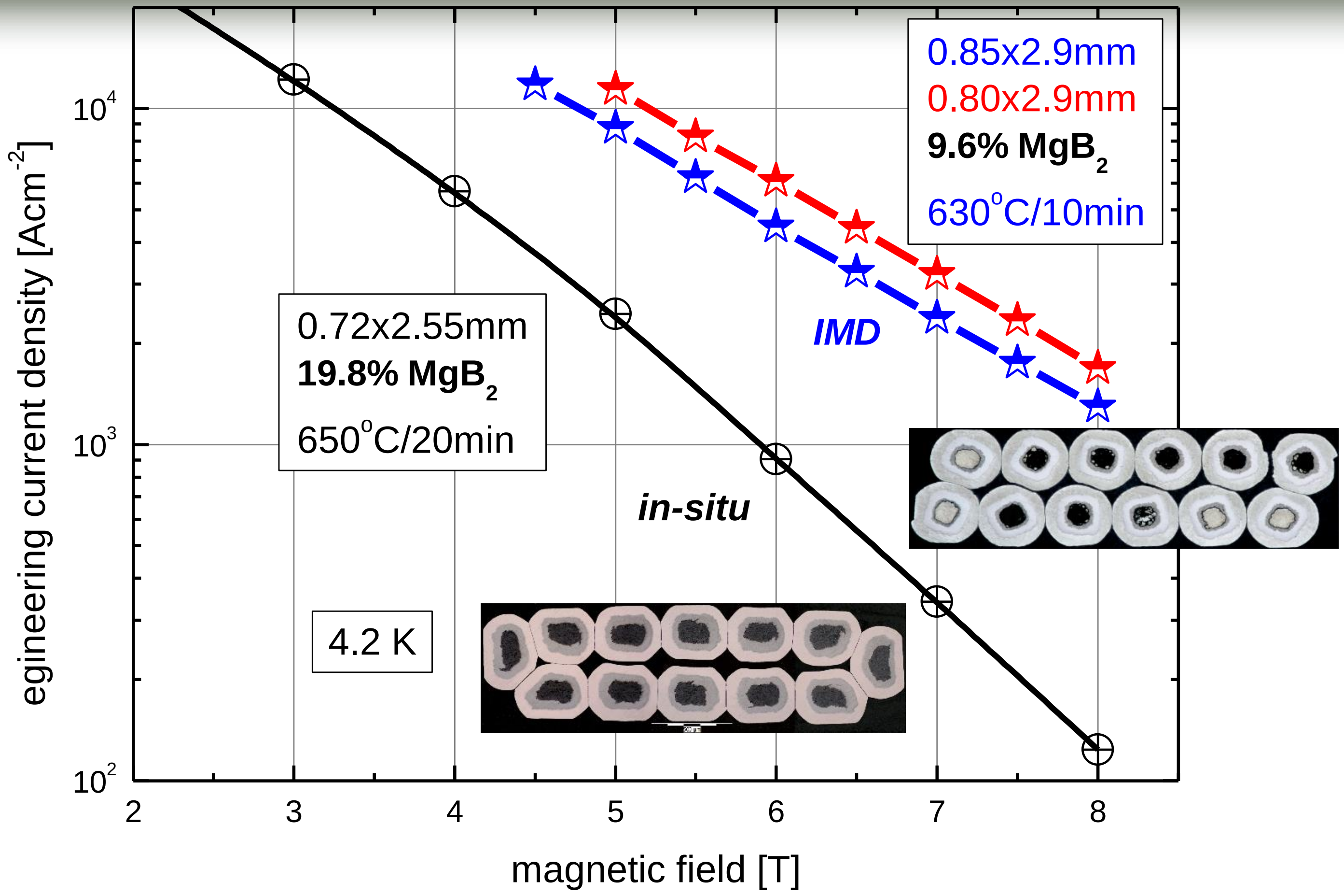
Ta-barriers of as-deformed Rutherford cable observed by X-ray micro-tomography





P. Kovac et al., submitted to *Sup Sci and Technol*

Enginnering current density of PIT and IMD cable

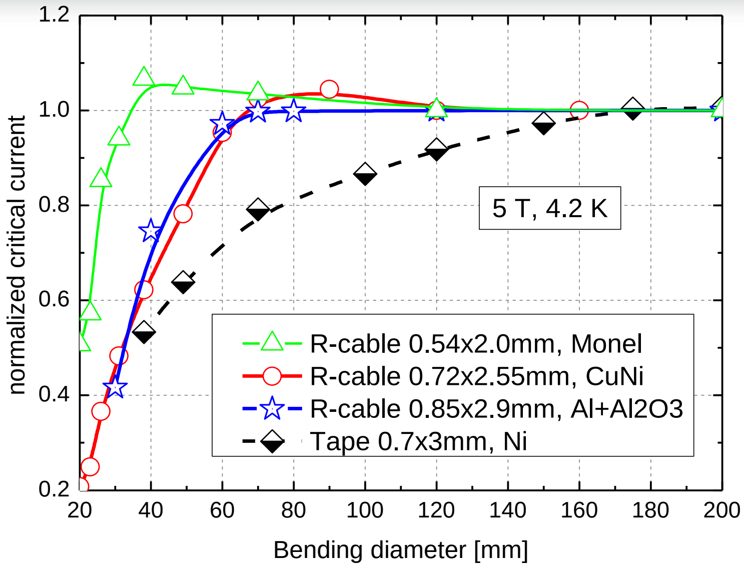


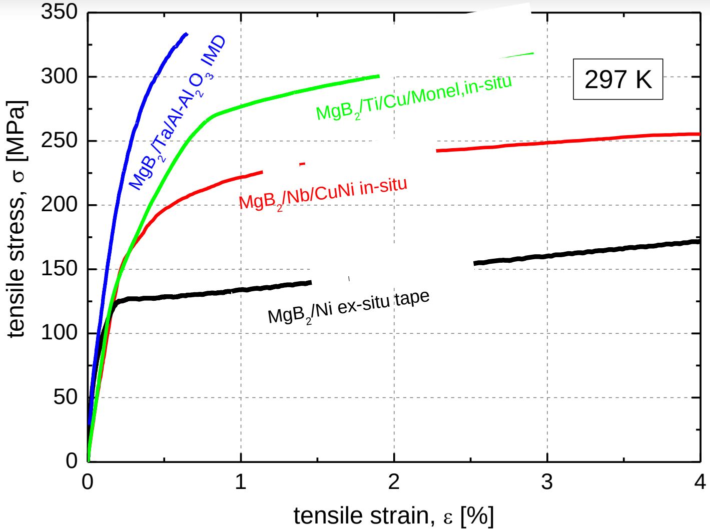
Rutherford cable made of IMD strands with **9.6% of MgB$_2$** has **10 times higher J_e** at 8 T in comparison to cable with PIT in-situ strands and doubled **MgB$_2$** content **19.8%**.

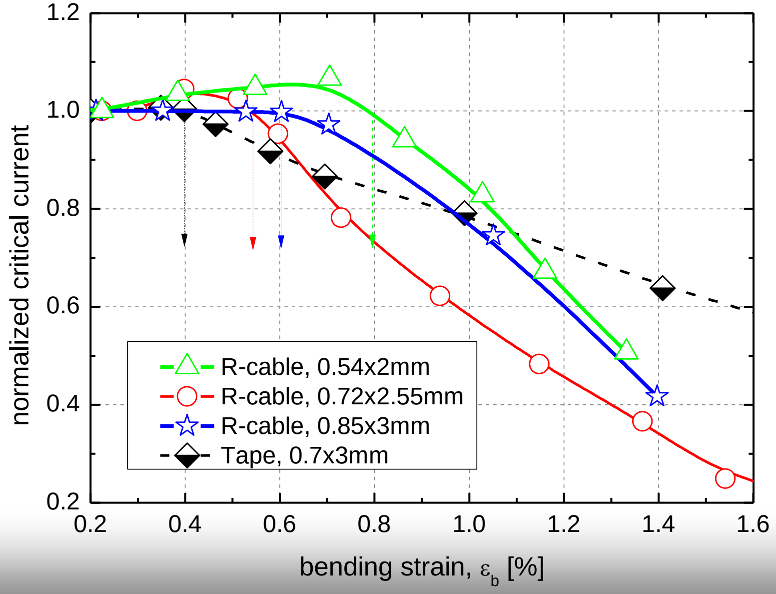
It allows to increase J_e values of IMD cable more and make it interesting for applications.

P. Kovac et al., submitted to *Sup Sci and Technol*

Tolerances of MgB$_2$ cables to bending

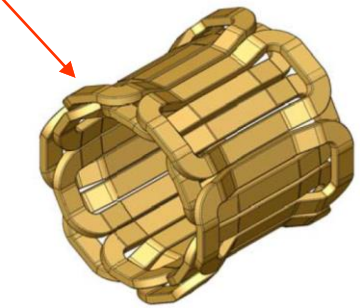






- **low I_c degradation** of Rutherford cable by bending **< 35 – 70 mm**
- important for **multi-pole generators** – low diameter **racetrack coil**

R&W coil
ID = 40mm
***R-cable** 0.54*
x 2.0 mm



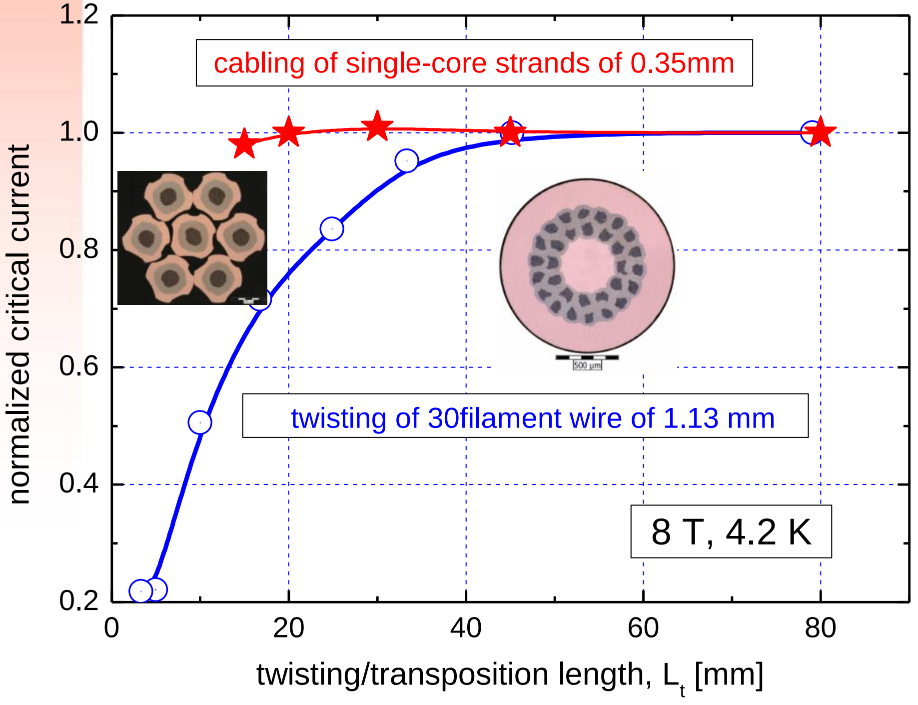
Kovac P et al. *Sup Sci and Technol* **30** (2017) in press

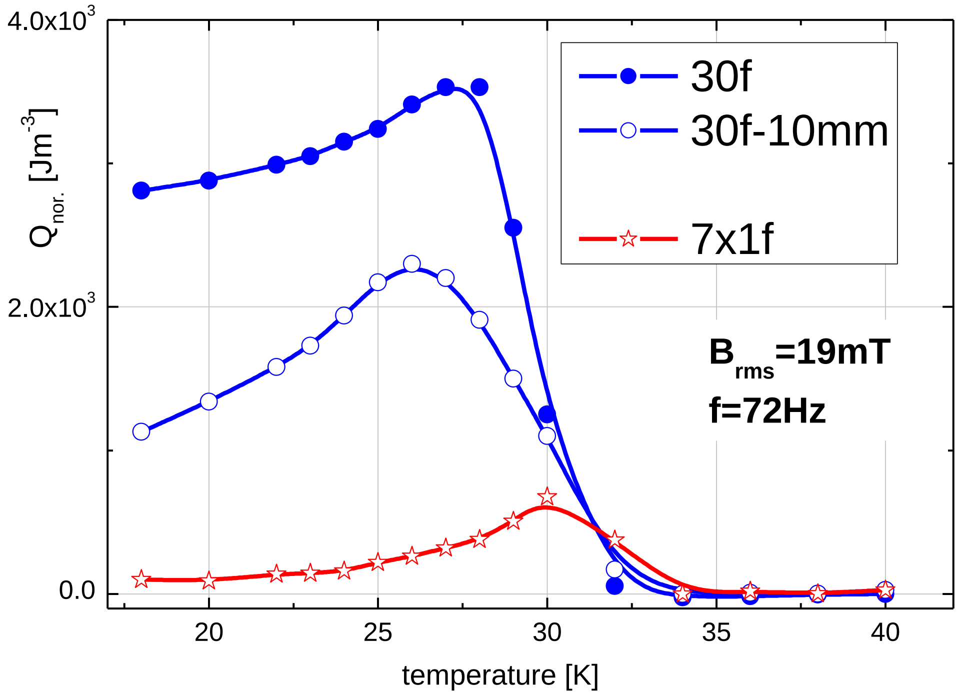
AC loss reduction, twisting or strands transposition

$$\frac{Q_C}{V} = \frac{B_a^2}{2\mu_0}\left[\frac{2\pi n_S \omega\tau}{1+\omega^2\tau^2}\right]$$

Time constant ***τ*****,**
important parameter

$$\tau = \frac{\mu_0}{2\rho_{eff}}\left(\frac{L_p}{2\pi}\right)^2$$



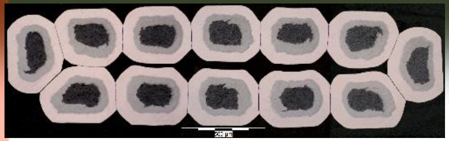


Strands **transposition** – more effective decoupling in comparison to filaments **twisting**:

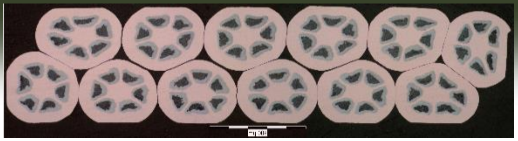
- large I_c degradation by twisting, nearly no by single-core strands transposition
- inter-filaments/ **inter-strands resistance**

J. Kovac et al., Physica C **495** (2013) 182

AC losses of Rutherford cables

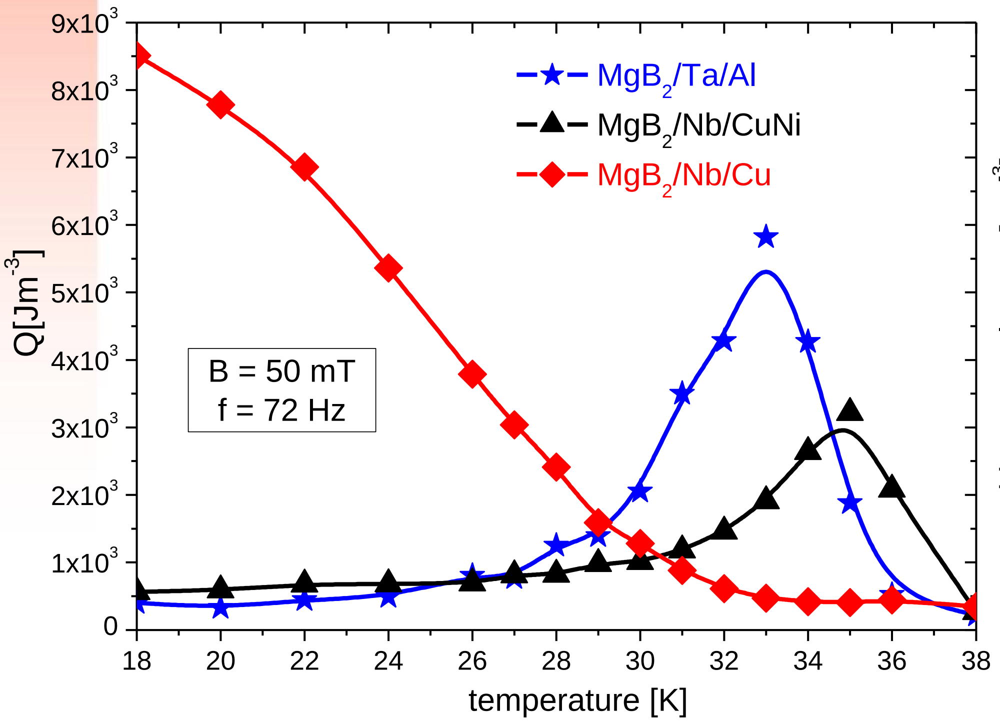


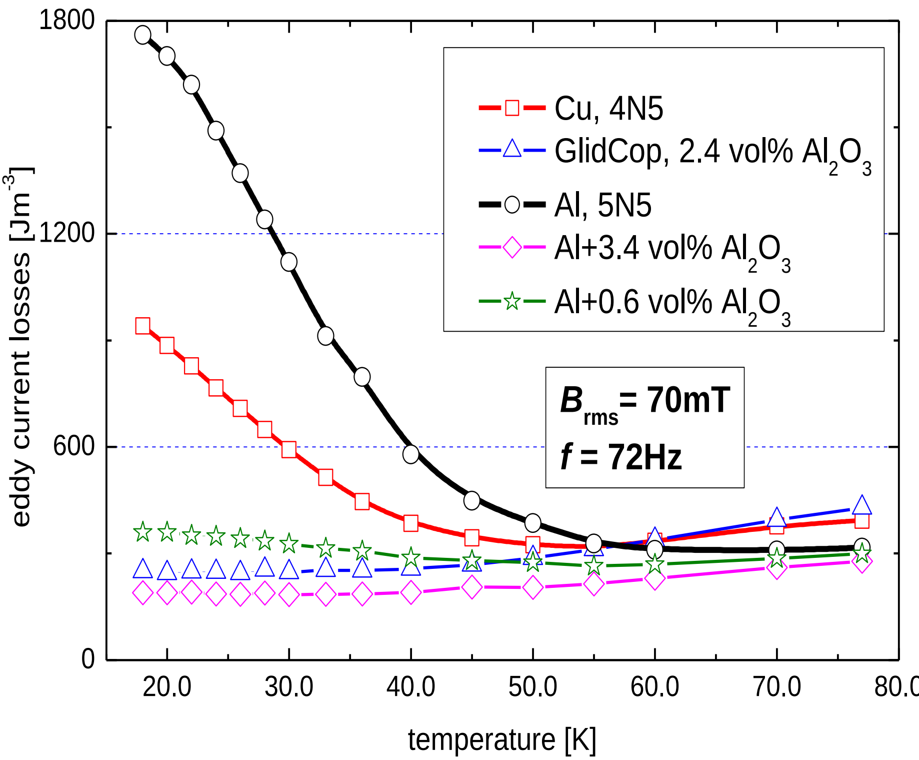
MgB_2/Nb/CuNi



MgB_2+C/Nb/Cu

MgB_2/Ta/Al-Al_2O_3

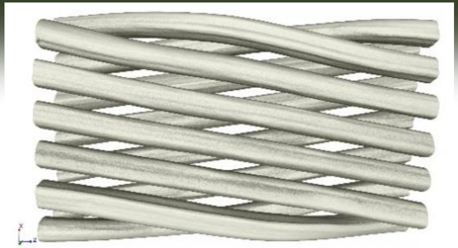


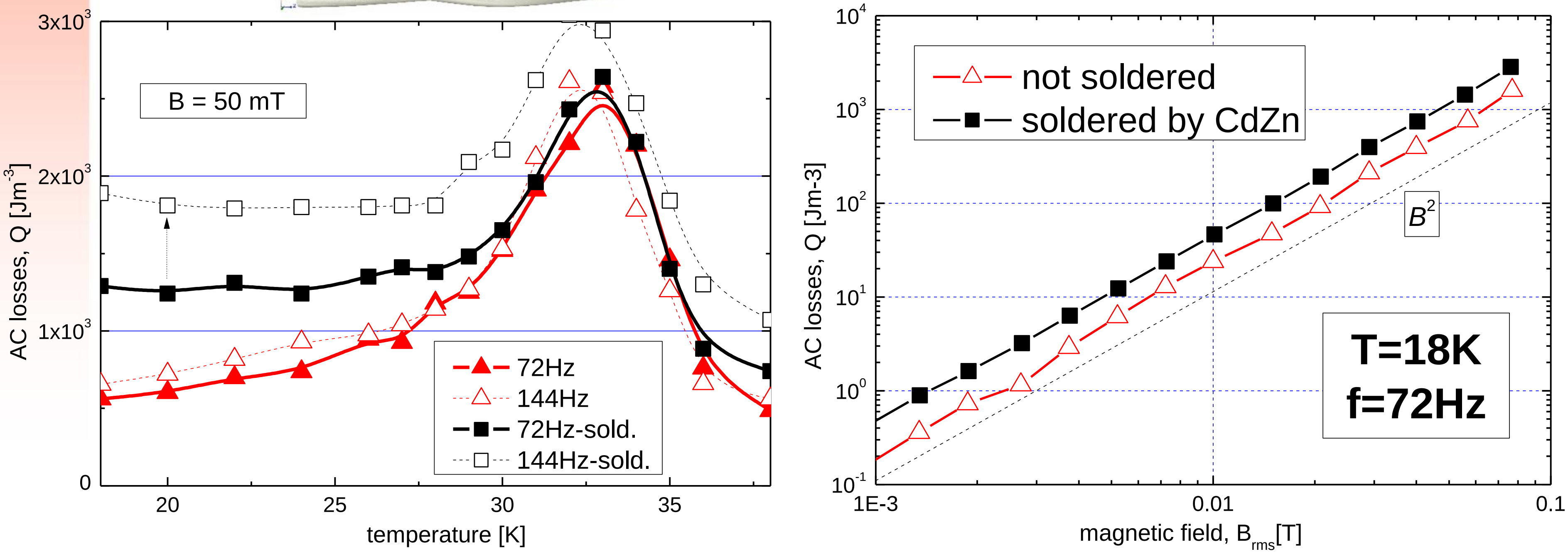


Total AC losses are affected not only by J_c of MgB_2 and fil. size, but also by outer sheath property - ***coupling and eddy current losses***

Eddy current losses - affected by *R*(*T*) *of applied sheath material,*
Al+Al_2O_3 – comparable with GlidCop

AC losses in free and soldered Rutherford cable





AC losses of **free Rutherford cable** 0.85 mm x 2.9 mm compared with the loss of **soldered-one** by CdZn, (a) temperature dependence of Q at 72 Hz and 144 Hz, (b) field dependence of Q at 34K and 72 Hz.

It demonstrates clearly the possibility of **decreased coupling losses** of Rutherford cables in comparison to a monolithic multi-core wires.

P. Kovac et al., submitted to *Sup Sci and Technol*

Conclusions

- **Rutherford MgB_2 cables** enable up-scaling of current **and densification** of powder by rolling is considerably **increasing critical currents** of as-drawn strands (***doubled*** J_e of cable).
- **MgB_2 cables** made of **IMD strands** have substantially higher engineering current density in comparison to PIT ones.
- Flat cables have **low I_c degradation by bending** stress (< *35 mm for - 0.3 mm strands, < 70 mm for 0.5 mm strands*).
- **MgB_2 cables** allows an effective **reduction of** coupling current **losses** without degradation of current currying capacity (in comparison to *twisting*).
- The **light and high current MgB_2** Rutherford cables with Al sheath can be attractive for applications where **the mass of system is important** issue (e.g. offshore wind turbines, aircraft engines and any of space applications).