TMC - A low-cost high-field conductor

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TMC and superconductivity

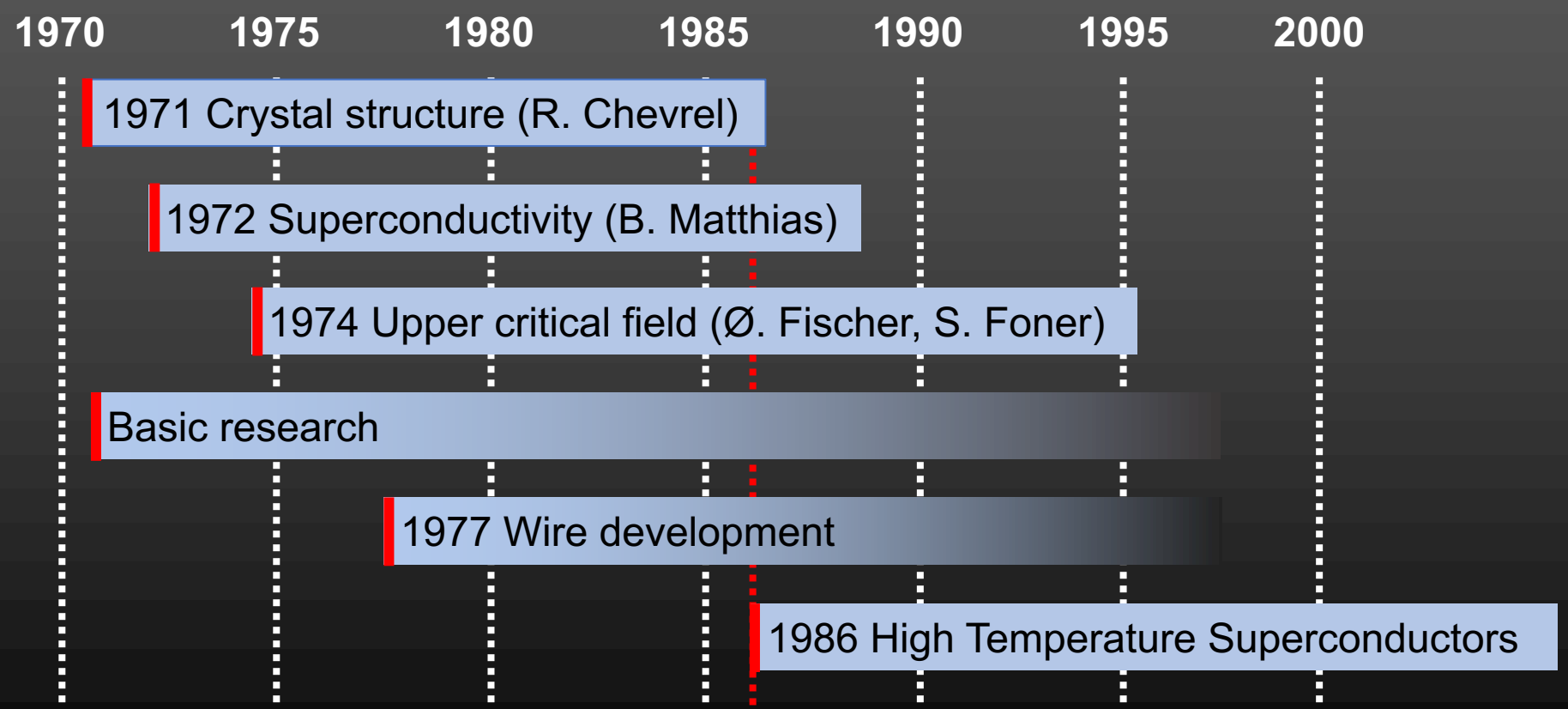
TMC = **T**ernary **M**olybdenum **C**halcogenide

$PbMo_6S_8$

$T_c \leq 15$ K

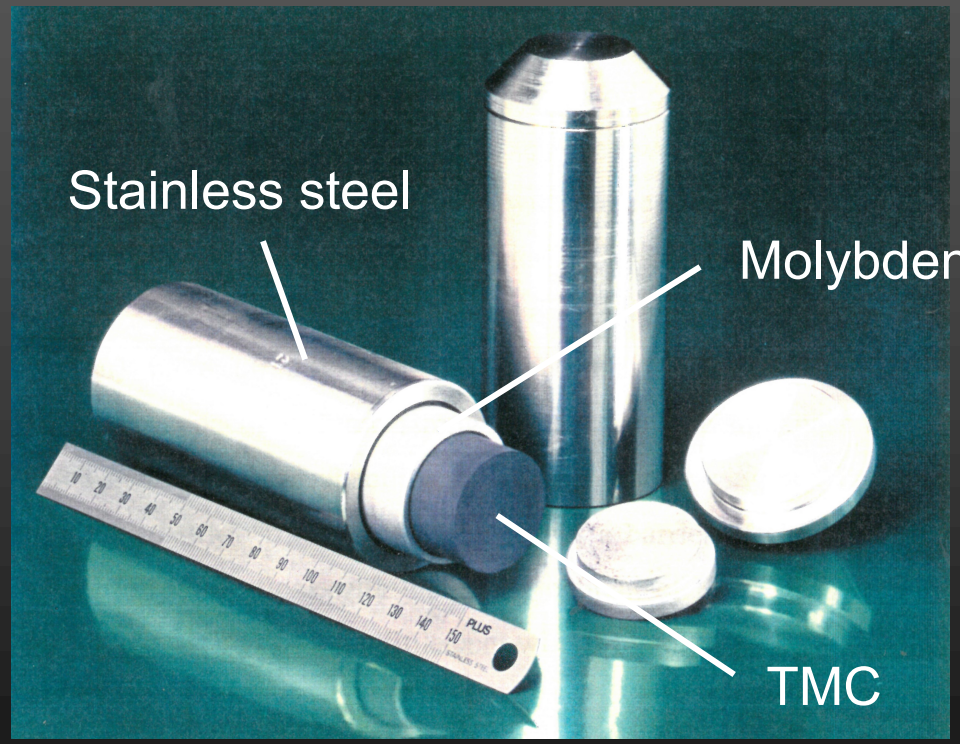
$B_{c2}(4.2\ K) \sim 51$ T

TMC - history


1970
1975
1980
1985
1990
1995
2000
1971 Crystal structure (R. Chevrel)
1972 Superconductivity (B. Matthias)
1974 Upper critical field (Ø. Fischer, S. Foner)
Basic research
1977 Wire development
1986 High Temperature Superconductors

1st stage: monofilamentary wire

Extrusion billet: OD 50 mm, length 100 mm (~ 1.5 kg)



R. Grill et al. Proc. Plansee Seminar 1989

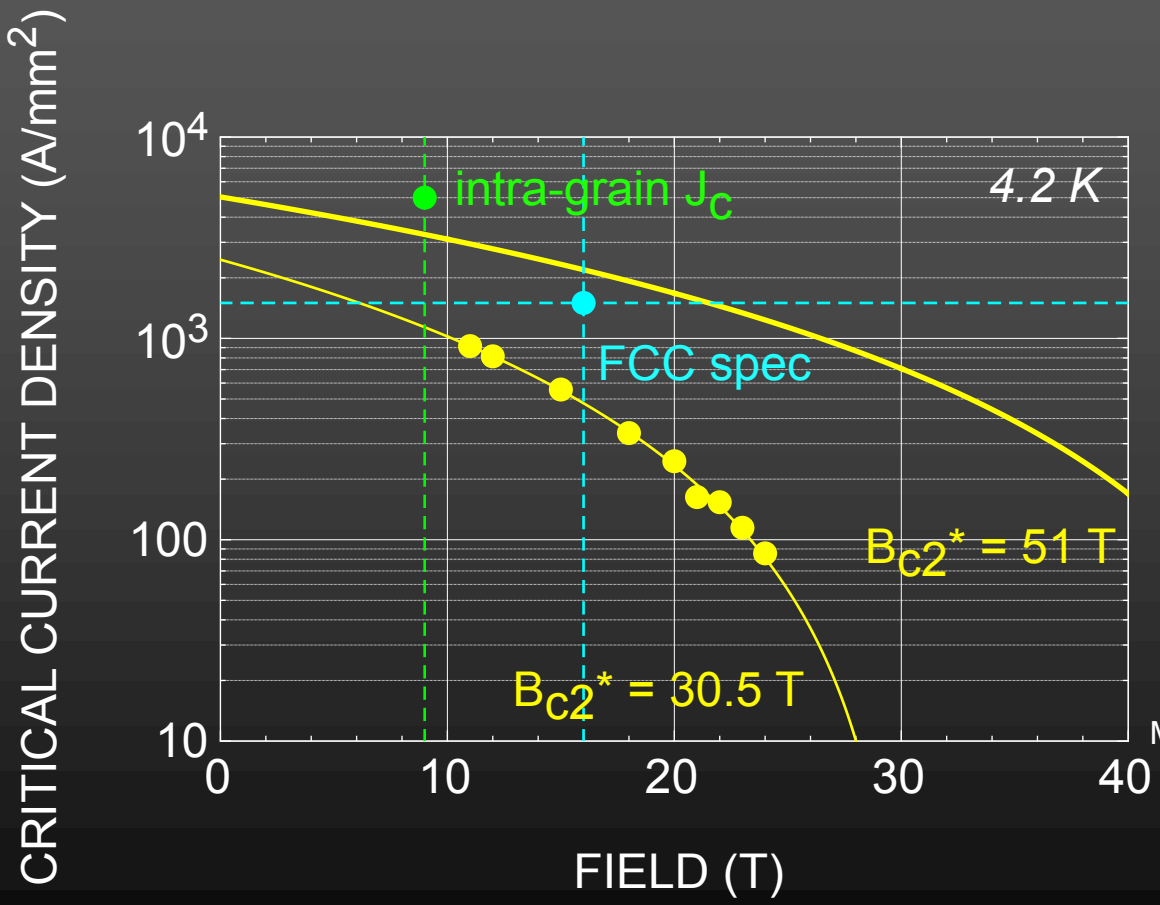
Powder in tube process - PIT

Manufactured on industrial fabrication line for Mo wires

~ 1 km with OD = 0.4 mm

TMC - critical current density

J_c in the superconductor cross section of a TMC (PMS) wire

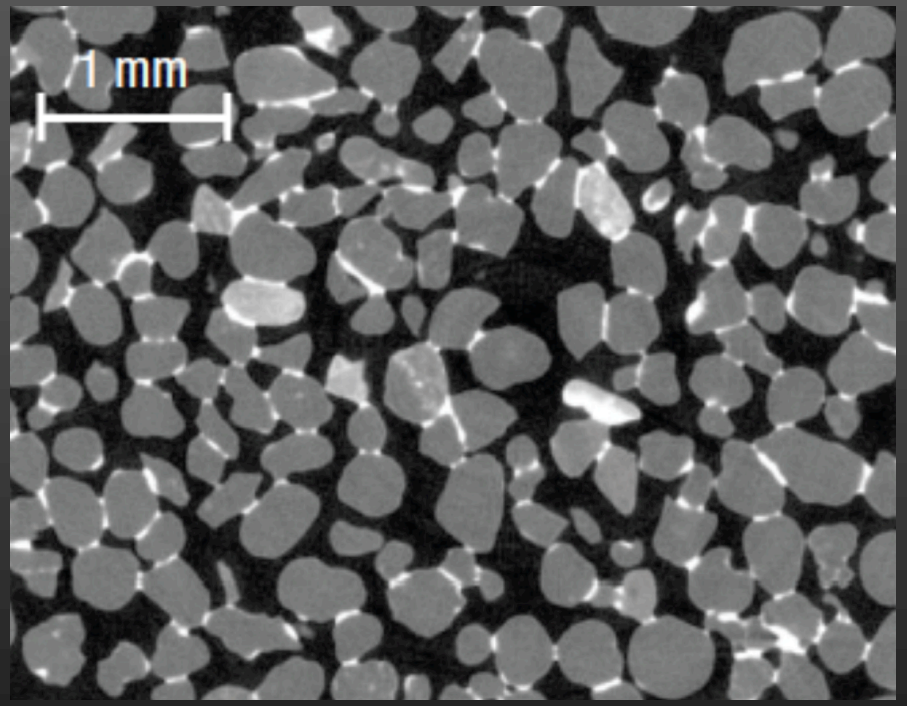


$$I_c B = C B_{c2}^{*2.4} b(1-b)^{2.2}$$

Measurement: N. Cheggour et al., JAP 81, 1997

Granular superconductor

Wet sand model system illustrated by X-ray tomography



M. Scheel et al., *Nature Materials,* March 2008

Critical current is restricted at grain boundaries:

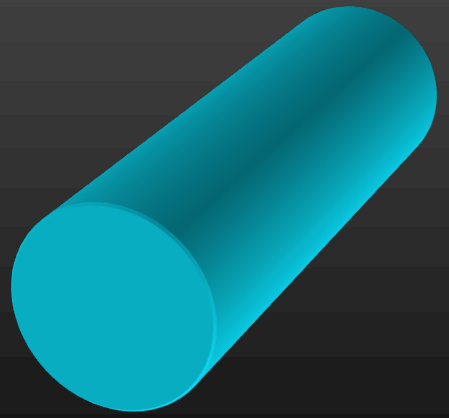
- Reduced contact area

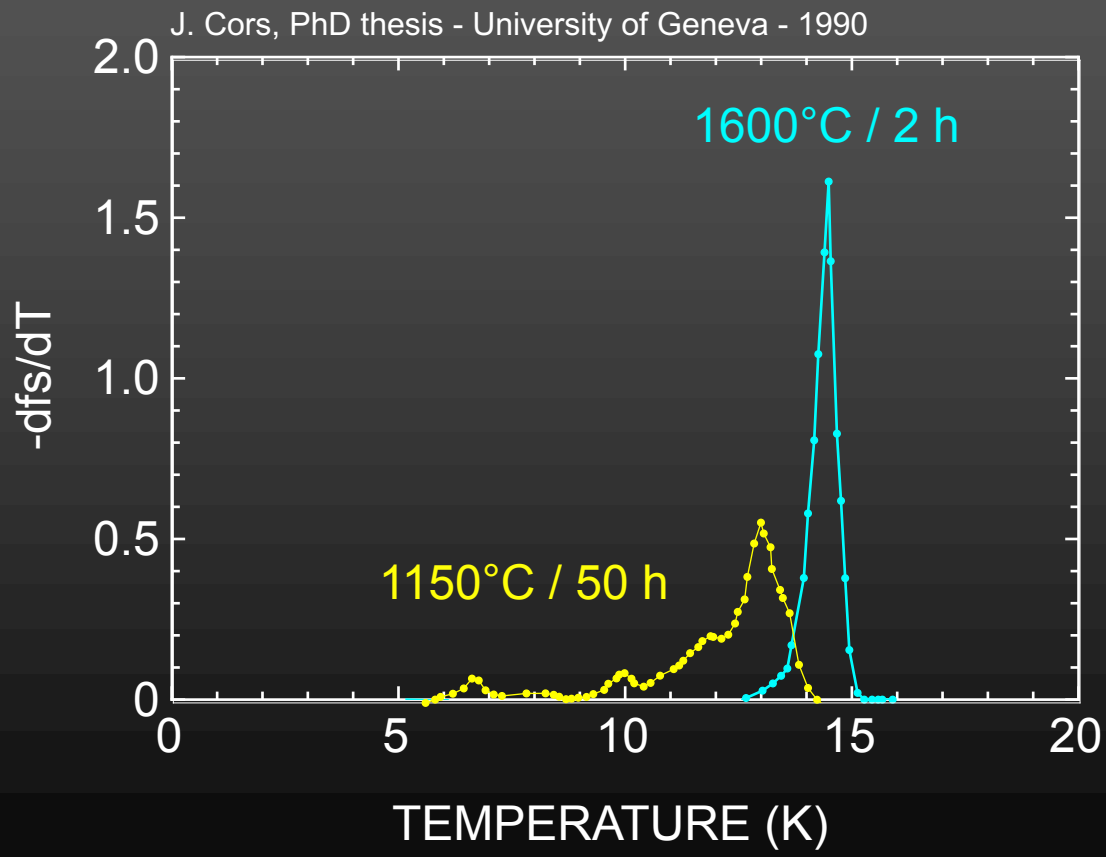
- Locally reduced T_c and B_{c2} (uncontrolled grain boundary diffusion)

New manufacturing process

Granted patents: US 10128428 (Nov. 2018)
EP 3105799 (Sep. 2019)

100% dense TMC bulk material





New manufacturing process

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EP 3105799 (Sep. 2019)

No reaction heat treatment !

Conductor price

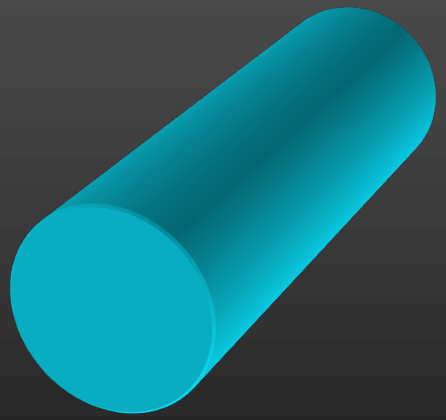
L. Cooley et al., SUST - 2005

Conductor price

Raw materials price x Production scaling factor P

Cost for raw materials - TMC bulk

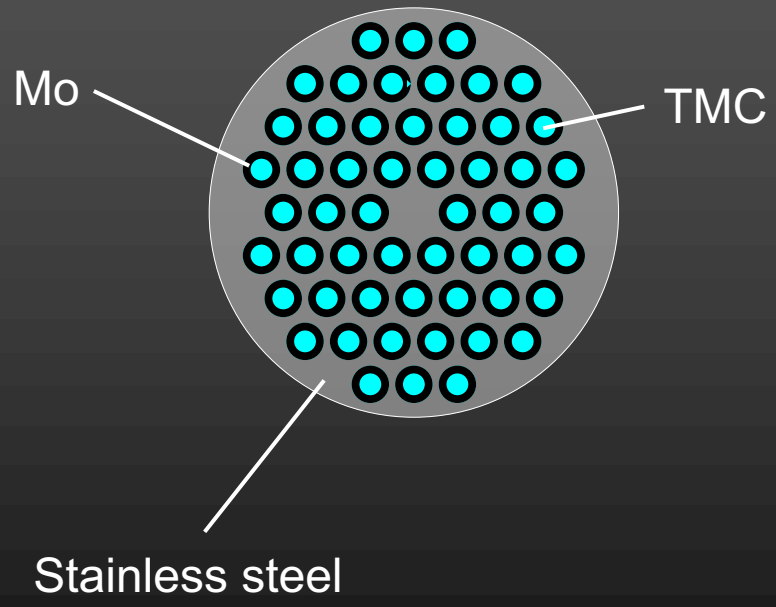
$PbMo_6S_8$ (PMS) bulk material (batch of 50 kg)



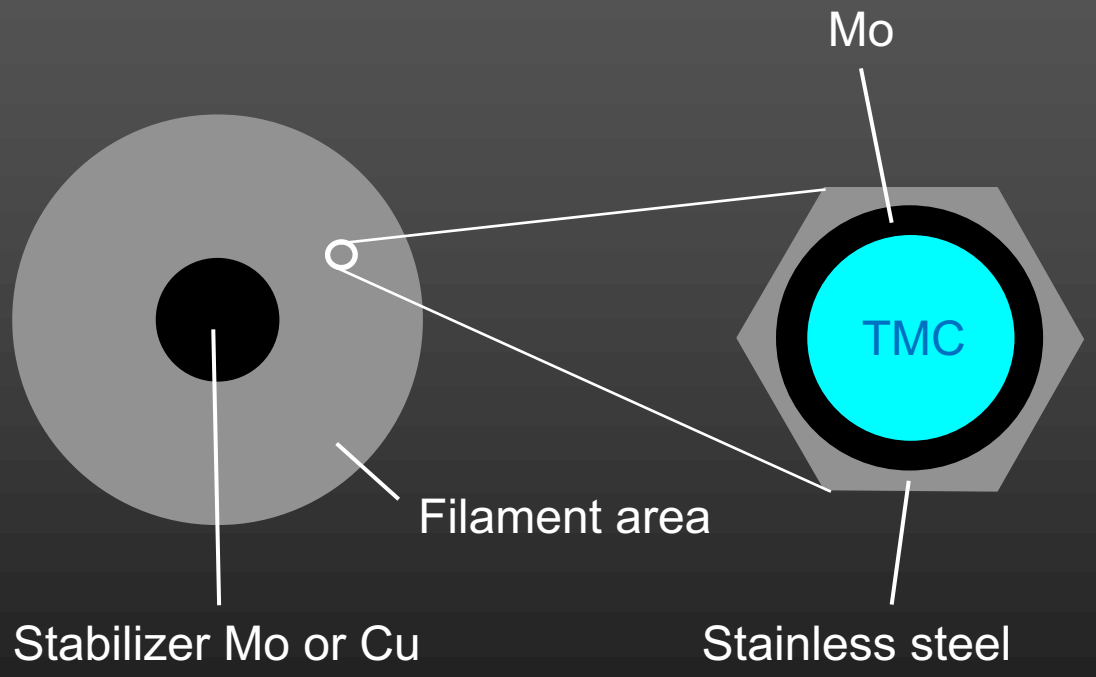
Constituent	Purity (%)	Price ($/kg)
Pb granulate	99.9	57
Mo powder	> 99.95	77
S powder	99.5	30
$PbMo_6S_8$		**61**

Conductor layout

MRI



HEP



Conductor price

Conductor price = raw materials price x production scaling factor P

Superconductor	Raw materials ($/kg)	P	Conductor price ($/kg)
TMC (PMS)	49 - 98[a]	3.3	160 - 325[a]
NbTi (LHC dipole)	61[b]	3.3	201[b]
N_3Sn (ITER poloidal)	120[b]	7.8	940[c]

a) Data for a multifilamentary TMC superconductor (MRI - HEP)

b) Data from L. Cooley et al. (SUST 2005) + inflation per CPI 2019

c) Data from Fusion4Energy, Barcelona

Performance index

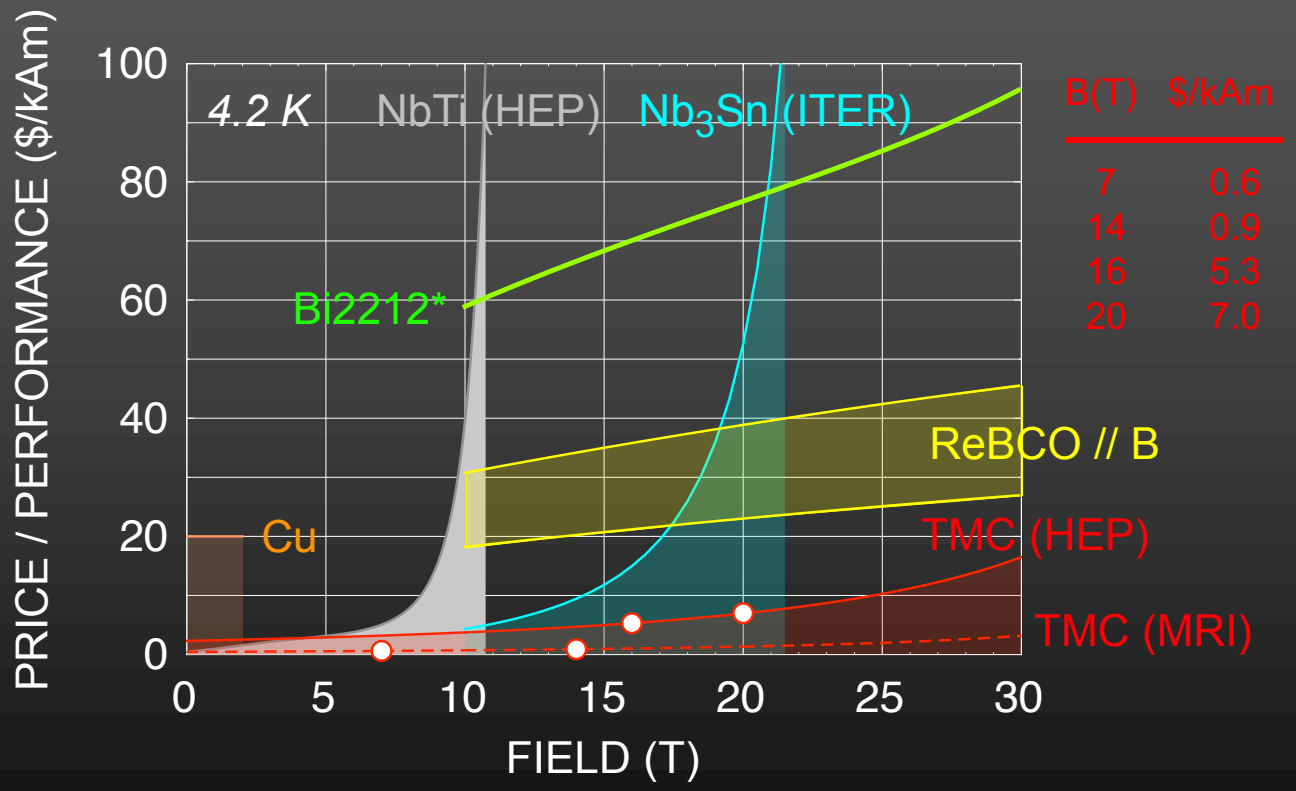
https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots - April 2018

$$\$/kAm = (\frac{\rho}{J_{eng}}) \times \$/kg$$

Superconductor	g/cm^3	$/kg
NbTi-LHC (R=1.8)	8.0	195
Nb_3Sn-ITER (R=1)	9.1	940
Bi2212 (R=4)	8.6	$10'360_{70\$/m}$
ReBCO	8.9	$8'220_{88\$/m}$ - $13'890_{50\$/m}$
TMC (MRI - HEP)*	7.2 - 8.0	160 - 325

*Production scaling factor = 3.3

R = stabilizer area / non-stabilizer area



* D. Larbalestier et al., MT25, 2017

Timescale

Immediate

- Identify industrial wire manufacturer

Three to four years

- TMC bulk material with small T_c distribution
- Multifilamentary wire > 1 km length
- Critical current density as forecasted or better
- TMC wire commercially available

Conclusions

- TMC may be considered as “NbTi for high fields”

- Magnet winding like NbTi (limited by bending strain)

- Cost efficient, starting above 5 T

- New manufacturing process ready for licensing (eventually for purchase)