Towards an affordable FCC:
TMC superconducting wires as alternative?

B. Seeber

About TMC

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

$M_xMo_6X_8$

M: chemical element

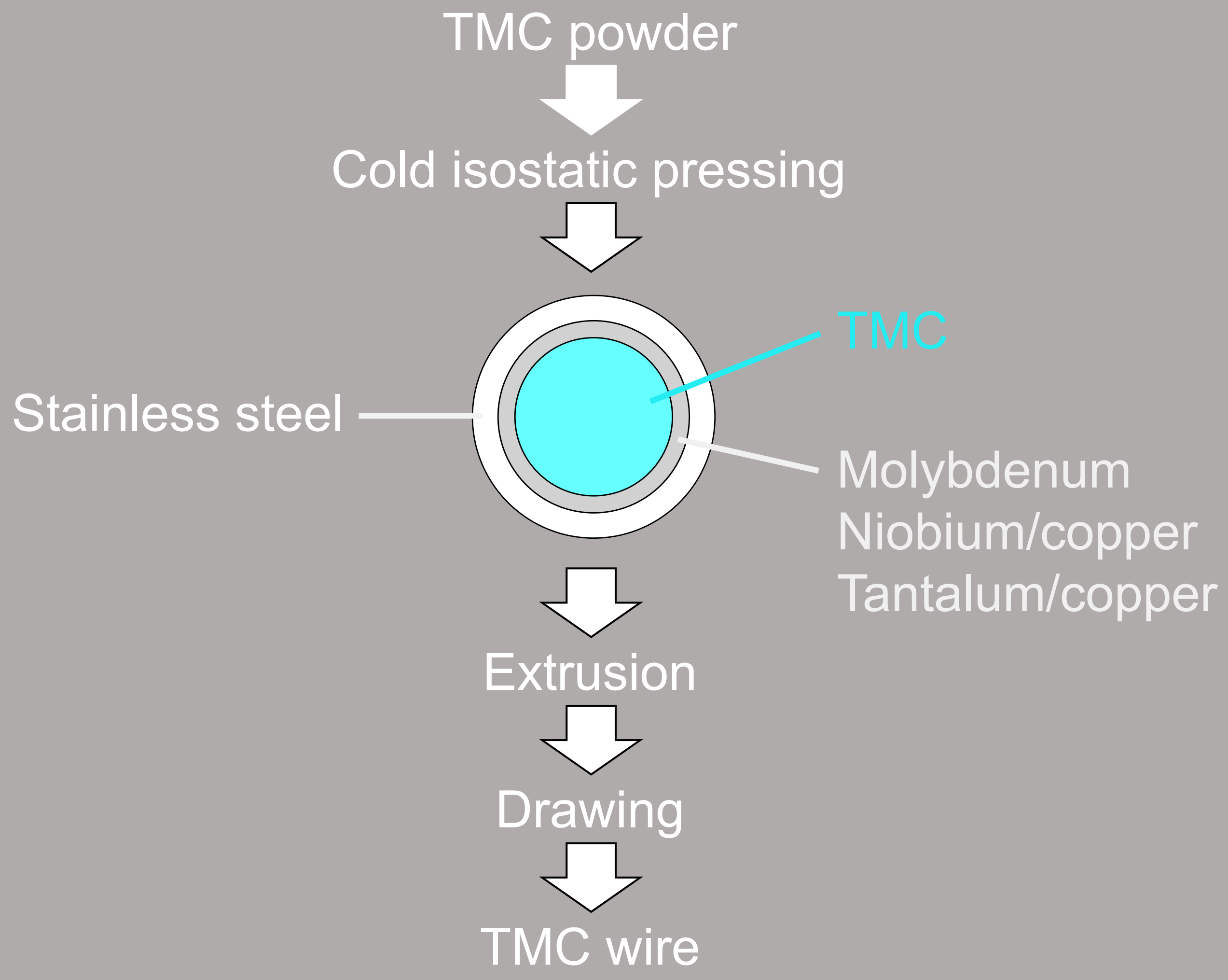
X: S, Se and Te

Most important for superconductivity

Compound	**T_c (K)**	**B_{c2} @ 4.2 K (T)**
$PbMo_6S_8$	15	51
$SnMo_6S_8$	14	~ 30

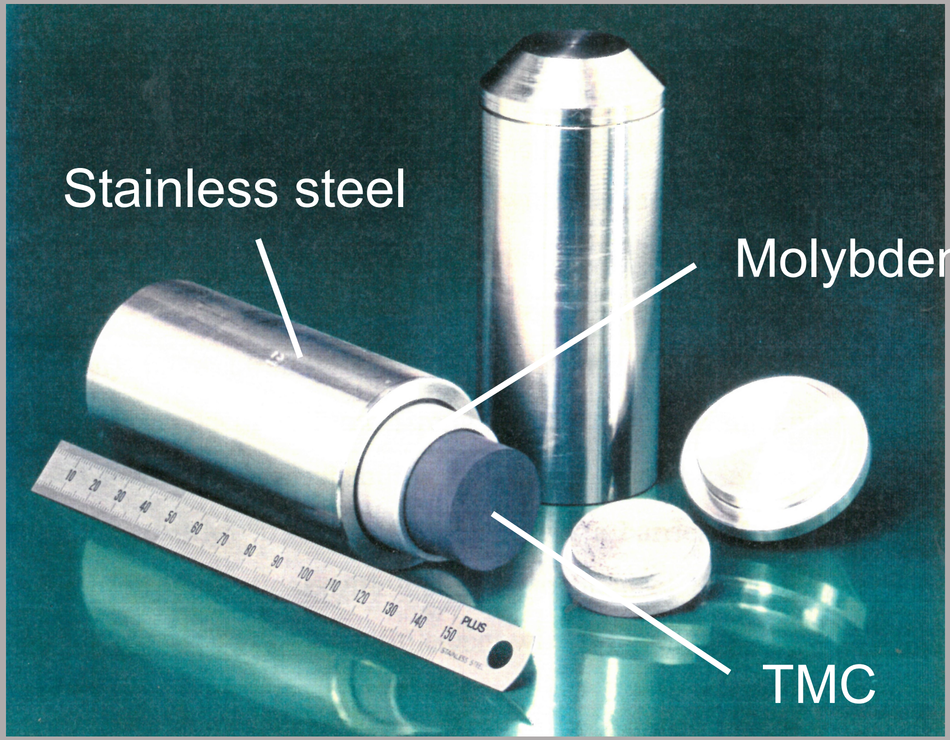
1^{st} stage: monofilamentary wire

PIT - process



1st stage: monofilamentary wire

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



R. Grill et al. Proc. Plansee Seminar 1989

~ 1 km with OD = 0.4 mm

PLANSEE

FCC Week 2017 (A. Ballarino)

Development targets - Nb_3Sn (starting with a 4 years program)

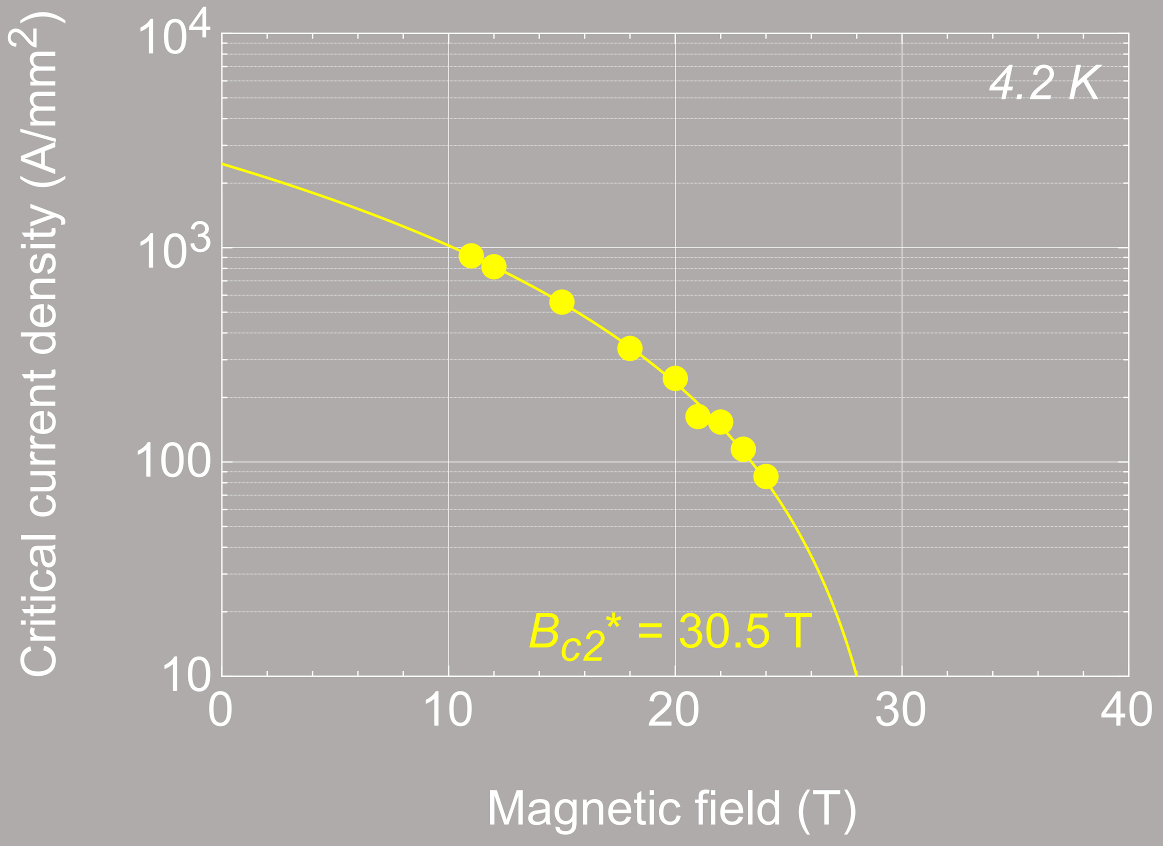
Wire diameter	mm	**~ 1**	
Non-Cu J_c (16 T, 4.2 K)*	A/mm²	**≥ 1500**	**Focus is on J_c**
~~**μoΔM(1 T, 4.2 K)**~~	~~mT~~	~~**≤ 150**~~	
~~**Deff**~~	~~μm~~	~~**≤ 20**~~	**≤ 50**
RRR	-	**≥ 150**	
~~**Unit length**~~	~~km~~	~~**≥ 5**~~	**≥ 0.1**
Cost	Euro/kAm**	**≤ 5**	

*J_e ~ 600 A/mm²
*Cu:non Cu ~ 1
** 16 T, 4.2 K

Process shall enable scalability and have potentially low cost for large production

Critical current density

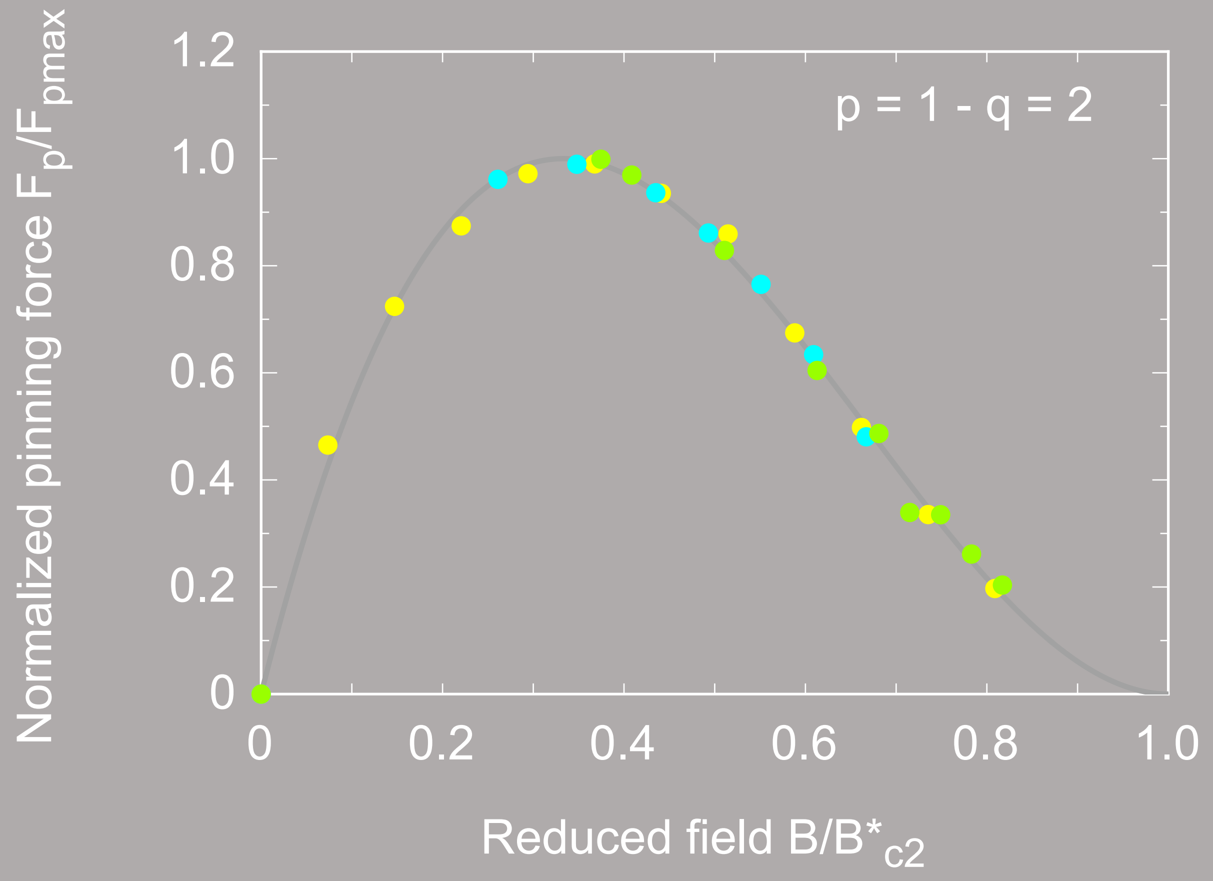
J_c in the superconductor cross section of a TMC wire (PMS)



N. Cheggour et al., JAP 81, 1997

Master scaling curve

TMC wires (PMS) with different layout

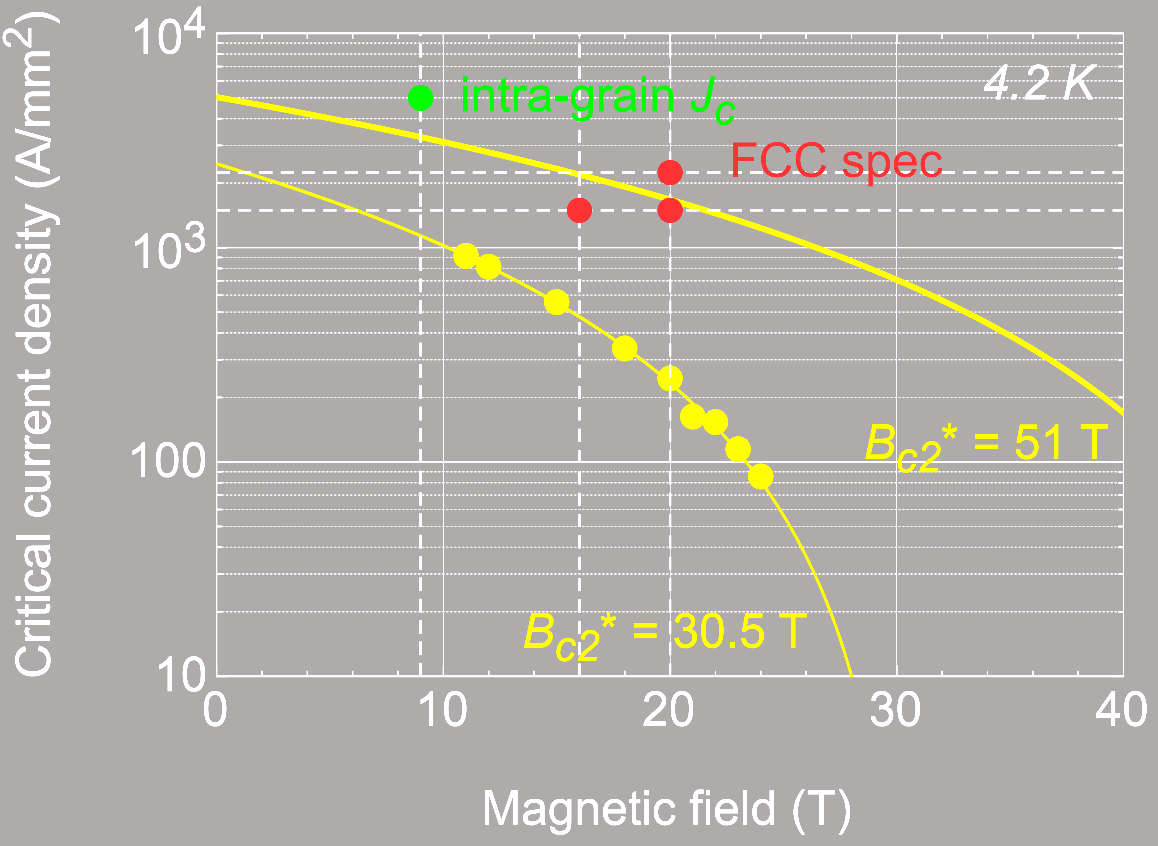


$$F_p = I_c B = C B_{c2}^{*2.4} b^p (1-b)^q$$

- W. Goldacker (IEEE Trans. Mag. 1991)
- Y. Kubo (Cryogenics 1993)
- N. Cheggour (JAP 1997)

Critical current density

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

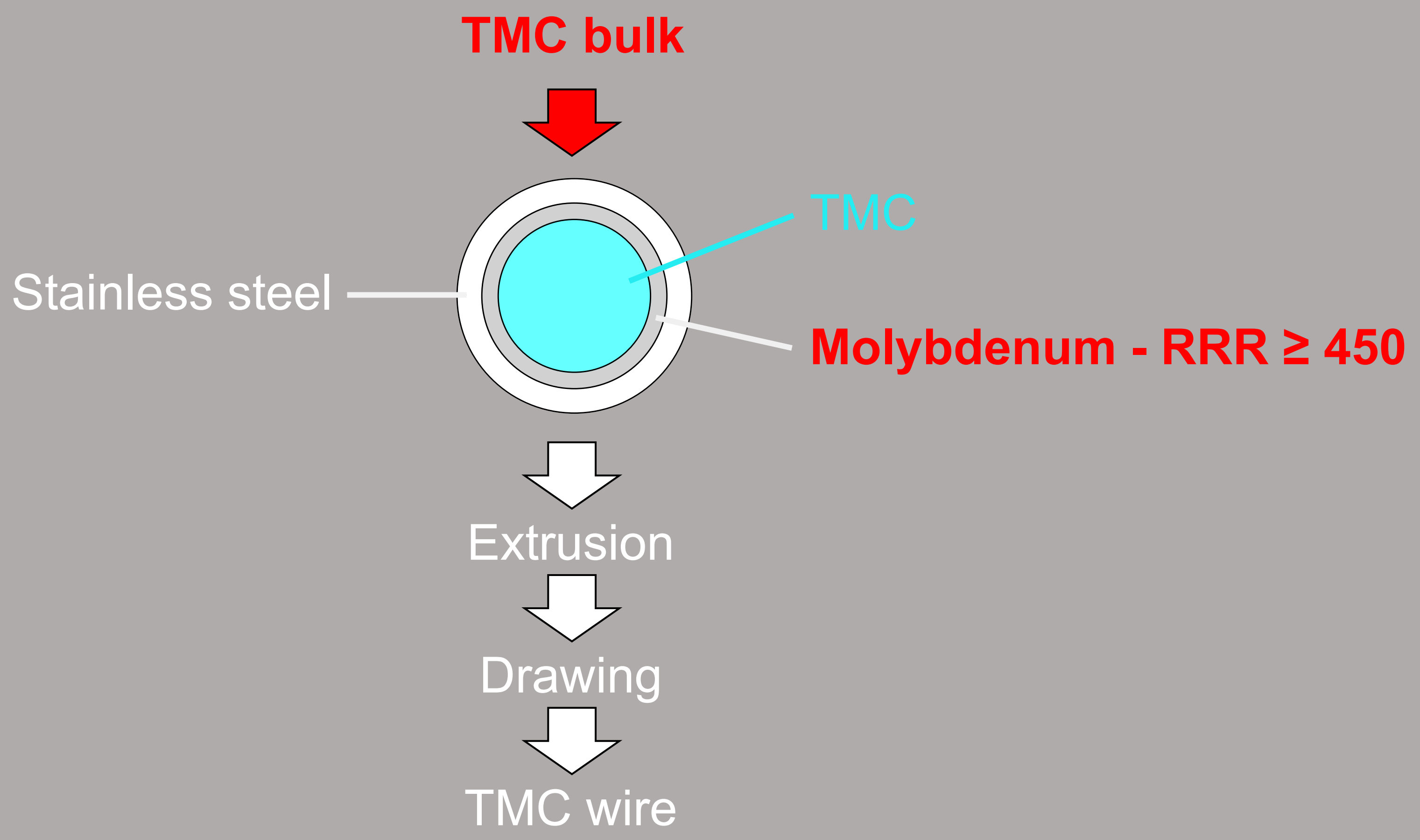


$$I_c B = C B_{c2}^{*2.4} b (1 - b)^{2.2}$$

N. Cheggour et al., JAP 81, 1997

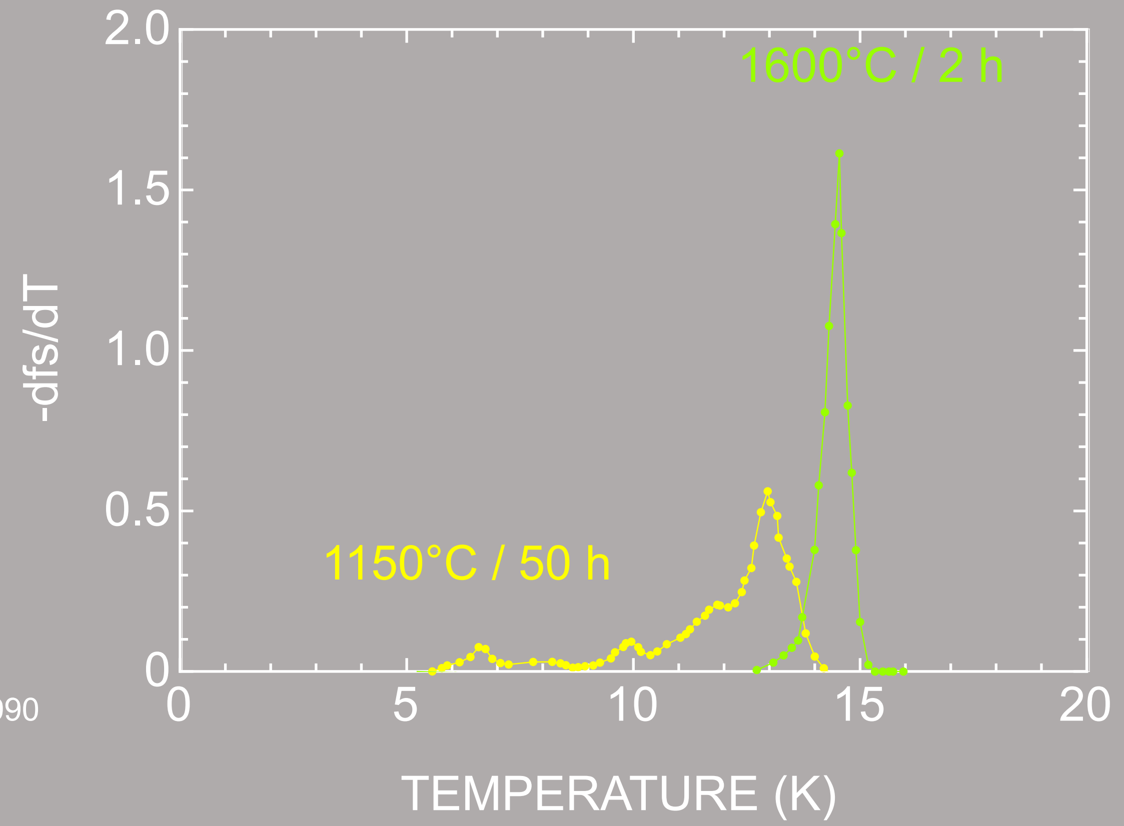
How to achieve prospective critical current density 1/2

New manufacturing process:
WIPO/PCT - WO 2015/117249 A1



How to achieve prospective critical current density 2/2

Distribution of the critical temperature of starting TMC powder ($PbMo_6S_8$) by specific heat measurement



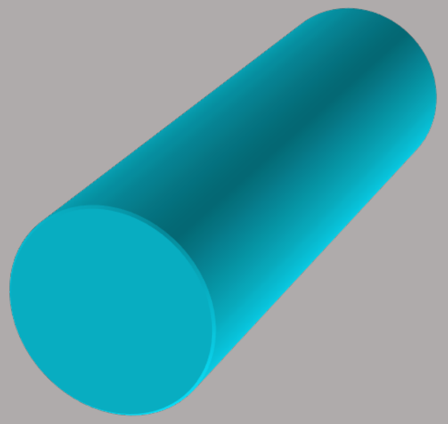
J. Cors, PhD thesis - University of Geneva - 1990

Costs

Costs, costs, costs …..

Cost for raw materials

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



Constituent	Purity (%)	Price ($/kg)
Pb granulate	99.99	65
Mo powder	> 99.95	77
S powder	99.99	101
$PbMo_6S_8$		81

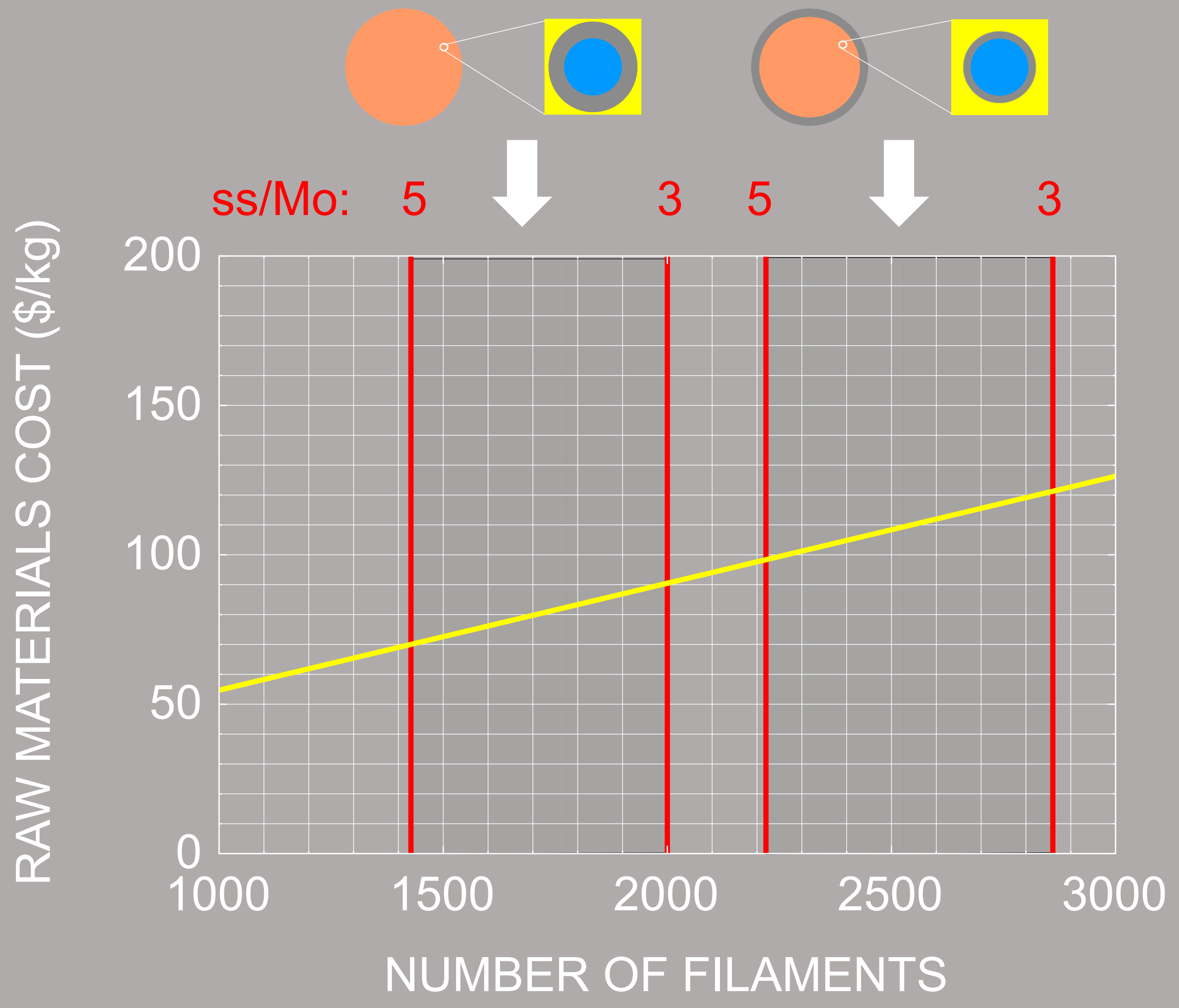
Cost for wire raw materials

OD (TMC wire): 1 mm

OD (TMC filament): 10 μm

Stabilizer/sc fraction: 1

OD (Mo barrier): 14.1 μm / 12.2 μm



Cost for wire raw materials

L. Cooley (SUST 2005)

(C) Costs	Nb47Ti (2005)	Nb47Ti (2017)	Nb_3Sn (2017)	$PbMo_6S_8$
Superconductor cost ($ kg^{-1})	105	137	260 - 377	81
Stabilizer cost ($ kg^{-1})	5	7	7	(101)
Reactants cost ($ kg^{-1})	—	-	20 - 195	
Diffusion barrier cost ($ kg^{-1})	220	286	286 - 546	265
Ancillary materials cost ($ kg^{-1})	—	-	7	17
(D) Cost indices				
Raw materials ($ kg^{-1})	45	59	95 - 138	70 - 121

Purchase price

P = Production scaling factor

Superconductor	Raw materials ($/kg)	Purchase price ($/kg)	P
NbTi (LHC dipole)	59[a]	195[a]	3.3
N_3Sn (ITER poloidal)	116[a]	940[b]	8.1
TMC (PMS prospective)	70 -121[c]	350 - 605[c]	5

a) Data from L. Cooley (SUST 2005) corrected for inflation 2017

b) Data from Fusion4Energy, Barcelona

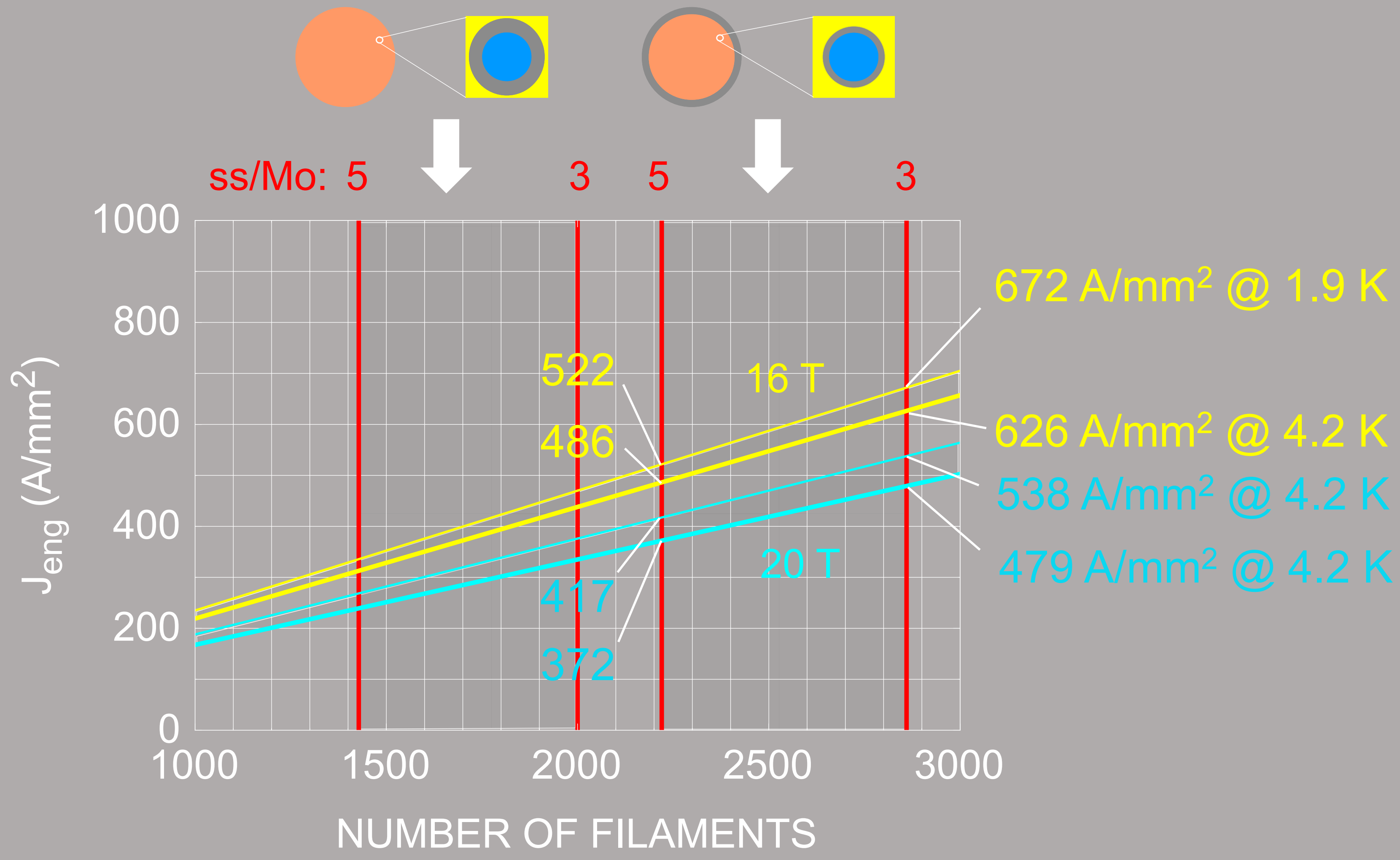
c) Data for a multifilamentary TMC superconductor (stabilizer/sc fraction = 1)

Performance index

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

Engineering current density

OD (TMC wire): 1 mm
Stabilizer/sc fraction = 1

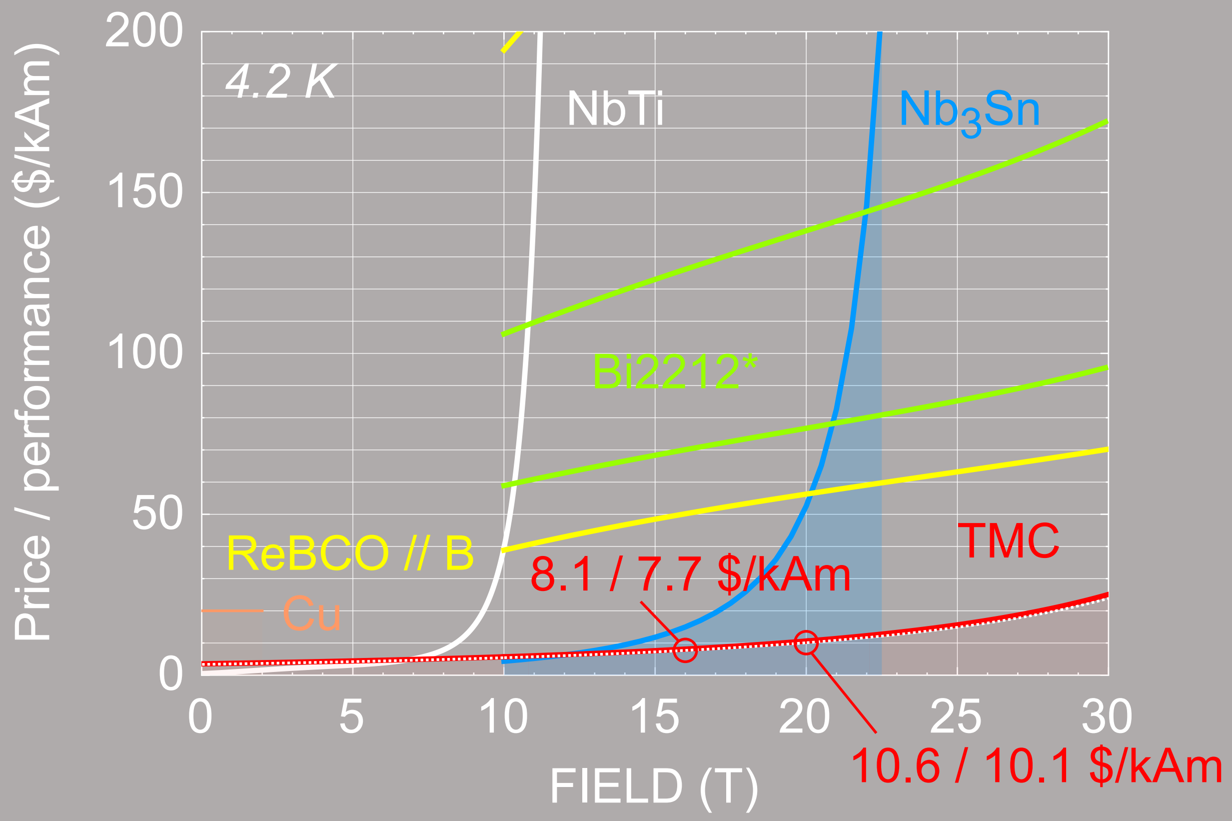


Performance index

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

Superconductor	g/cm³	$/kg
NbTi-LHC (R=1.8)	8.0	195
Nb_3Sn-RRP (R=1)	9.1	940
Bi2212 (R=4)	8.6	10'360
ReBCO	8.9	12'640
TMC (Mo/sc = 1)**	8.0	494
		605

**OD wire = 1mm
OD filament = 10 μm, 2220 and 2860 filaments
Production scaling factor = 5



* D. Larbalestier et al. *Nature Materials*, 2014 and MT25, 2017

Summary

- Isotropic (almost) upper critical field up to 51 Tesla @ 4.2 K
- **Critical currents may be substantially improved by new manufacturing process**
- Direct extrusion and wire drawing with round or rectangular cross section (almost like NbTi)
- **No reaction heat treatment after wire manufacturing**
- Winding of magnets is similar to that of NbTi (within limits)
- **TMC wires were already manufactured on industrial scale up to 1 km of length**
- The filament size can be adjusted within a wide range
- Yield strength R_{p02} is about 800 MPa @ 4.2 K (Nb_3Sn about 200 MPa)
- **Raw material costs for a TMC superconductor are between 70 - 121 $/kg (range of Nb_3Sn)**