Low Cost, High Current Superconducting Cables for Fusion

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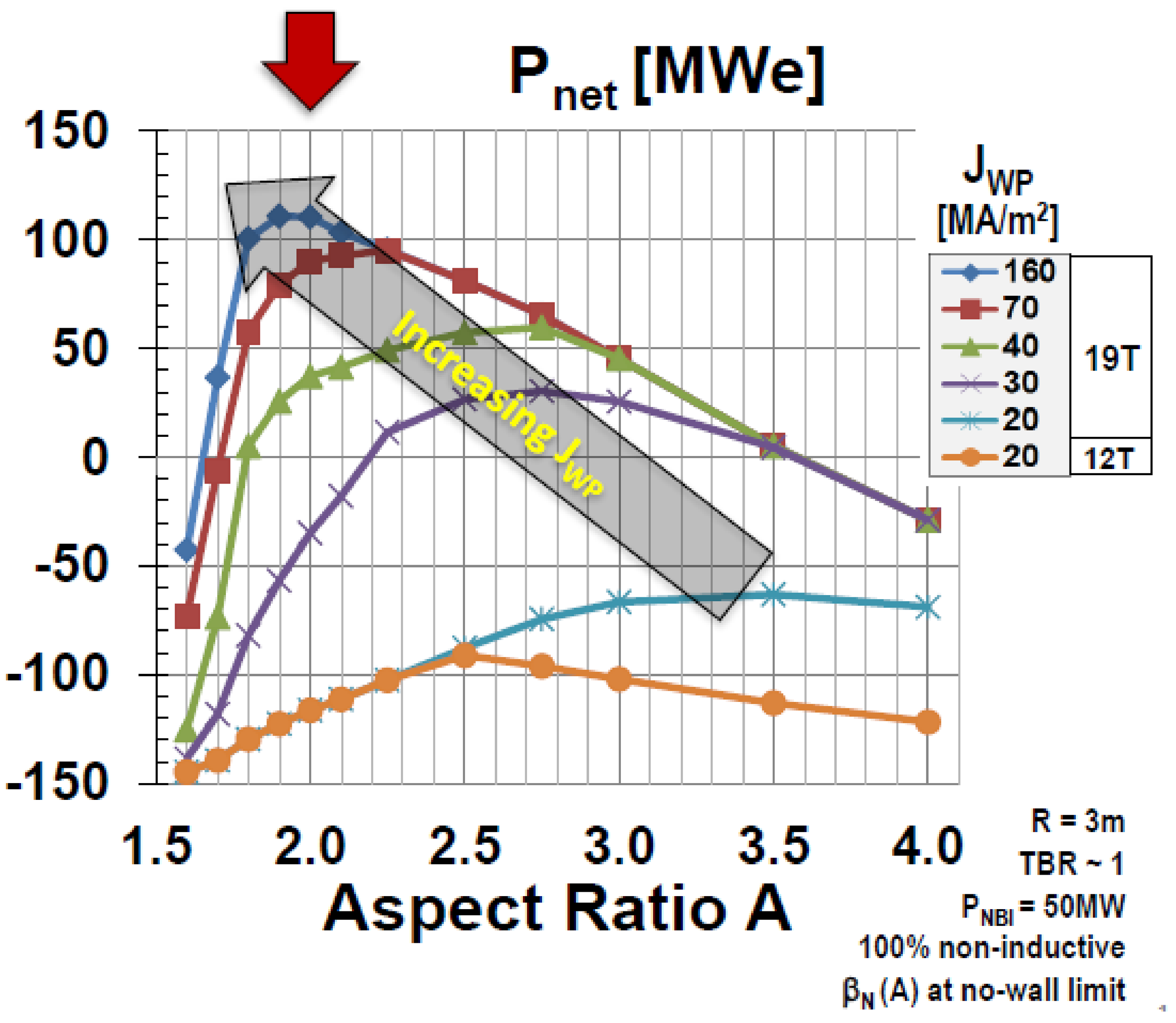
The challenge: Next generation fusion magnets for the Fusion Nuclear Science Facility (FNSF) or Pilot Plants beyond ITER are required to generate higher magnetic fields on coils using higher current density cables of coil winding in a smaller design space with affordable cost, compared to ITER. The high field and high current density magnets are particularly beneficial for low-aspect ratio "spherical tokamaks" (ST) and compact stellarators that PPPL is currently pursuing, due to their space constraints.

High field and high winding pack current density ***Need J_{WP} > 70 MA/m^2***

A ~ 2 attractive at high J_{WP}



Advancement of Nb_3Sn wires

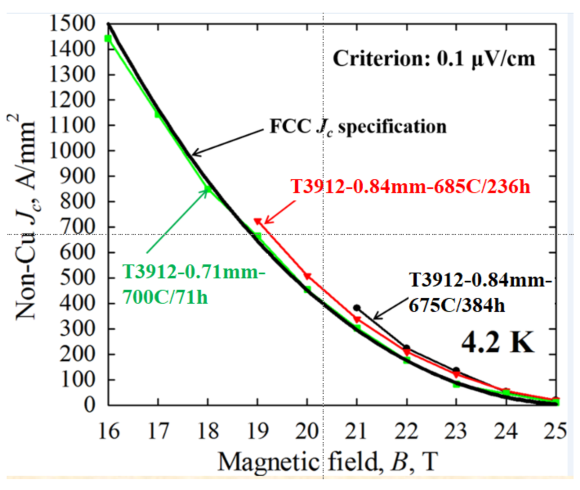
New advanced Nb_3Sn superconductor CICC can significantly impact next fusion magnet design for a compact FNSF and Pilot Plants.

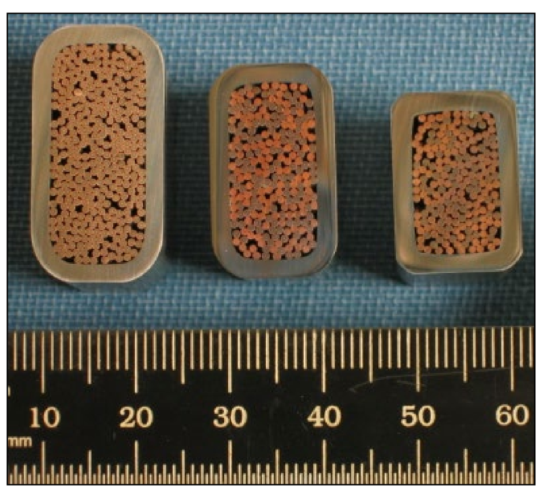
The high performance Nb_3Sn wire provides at least 3-5x higher critical current than ITER wires at (12T, 4.2K). The conventional ITER-Nb_3Sn cable-in-conduit conductors (CICCs) consists of hundreds multi-filamentary wires twisted together to form a high current cable can still be used as the mature technology for coil windings & performance optimization.

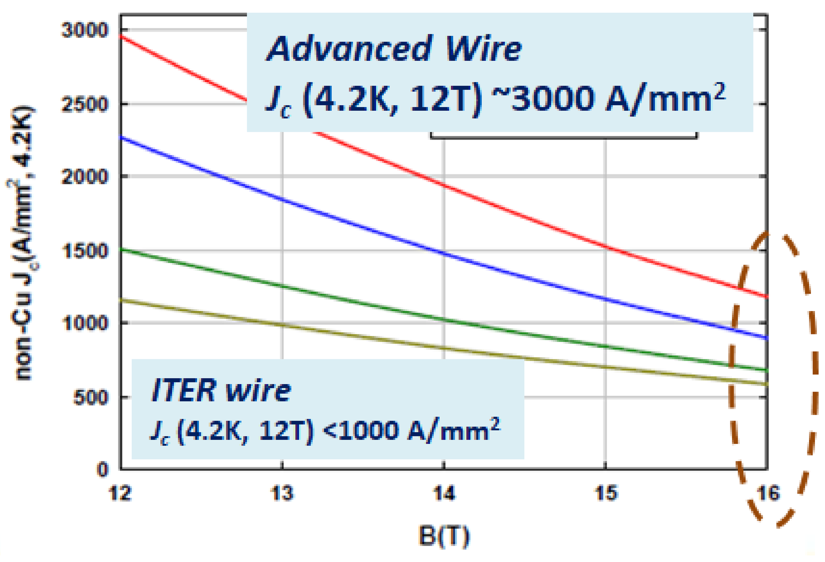
Conventional CICC of pancake or layer-wound hybrid winding. With new advances in high performance Nb_3Sn and mechanically enhanced Bi-2212 wires, next-gen tokamaks can be built with *commercially available wires of low cost to achieve >70 A/mm^2 winding current density*

Plasma radius R_0 = 1.2 m, Aspect ratio A = 2.4

Radial Build	ITER	1.2 m LM-ST	
R_0 (m)	6.2	1.2	
a (m)	2	0.5	
I_p (MA)	15	2	
I_{TF} (kA)	68	19.5	
no. TF coils	18	10	
no. of turn	134	170	
B_0 (T)	5.3	5.53	
R_i (m)	2.8	0.51	
B_i (T)	11.7	13.0	
D_{wire}	0.8	0.7	mm
Cu:non-Cu	1	1.0	
J_c (12T, 4.2K)	1000	3000	A/mm^2
J_c (16T, 4.2K)		1500	A/mm^2
I_{op} (A)	75.55	150.0	A
Nb_3Sn	900	130	
Cu	522	70	
I_TF_coil (kA)	68.00	19.5	kA
J_{WP}	23	74	A/mm^2



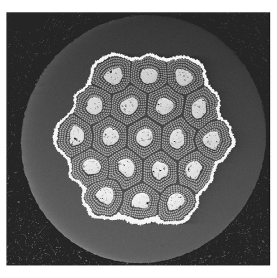
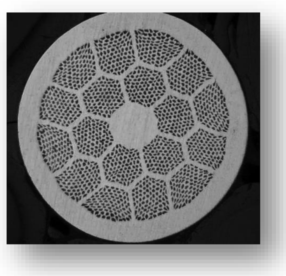




CS Example for Compact Spherical Tokamak

Table 2 PPPL CS coil conductor requirements versus 2212 state of the art transport properties

CS coil defining requirements			
Outer diameter	100 mm	Maximum Field	20 T
Inner diameter	for practicality, > 15 mm	Field ramp rate	5 to 10 T/s
Length	1100 mm	Total Current	1.6 x 10^7 A
Enclosed current area	46,000 mm^2	Operating temperature	4K, prefer greater, to 20K
Current densities needed at max field			
Jop coil	340 A/mm^2		
Jop cable	453 A/mm^2 (75% cable in coil)		**Je (4K) in leading edge 2212/Ag wire**
Je cable	604 A/mm^2 (Jop/Je = 0.75)		(1,700 and 1,190 A/mm^2 in 5T and 20T)
Je needed in wire	710 A/mm^2 (85% wire in cable)	**Versus**	1,070 A/mm^2 possible in 20T, reinforced

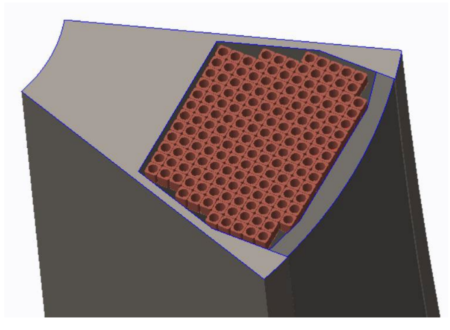



advanced Nb_3Sn Bi-2212

Prototyping and Testing of 10 kA cables to prove performance:

- Fabricate conventional CICCs using advanced Nb_3Sn wire, but 6-around-1 cabling pattern (with short twist pitch for stable mechanical performance proven by ITER CS)
- Heat-treat, test sub-winding in background field to validate performance

Cost: $300,000 ***Start in September 2019***
Schedule to build & test: 1 year after funding



Then build a prototype solenoid with hybrid winding:

- Build 13 T solenoid with 50 cm bore, 50 cm length
- Layer-wound hybrid coil comprising both Bi-2212 and Nb_3Sn sub-windings.
- *Outcome*: Prove hybrid-coil using conventional CICC ready for tokamak windings

Cost: $1,200,000
Schedule to build and test: 1 years after funding

Benefits to fusion program:

- Built prototype coil using existing mature cabling, jacketing and coil winding technology, remove stress management issue in HTS option strategy for >16 T toroids and solenoids.
- Prove achievable winding pack current density for windings for both ST and stellarators.
- Wires are commercially available now so performance achievable with relatively low cost.