SuperCIC: enhanced winding current density for high-field windings of tokamaks

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5 Lockheed Martin Aeronautics

Fusion is a staggering application for superconducting magnetics

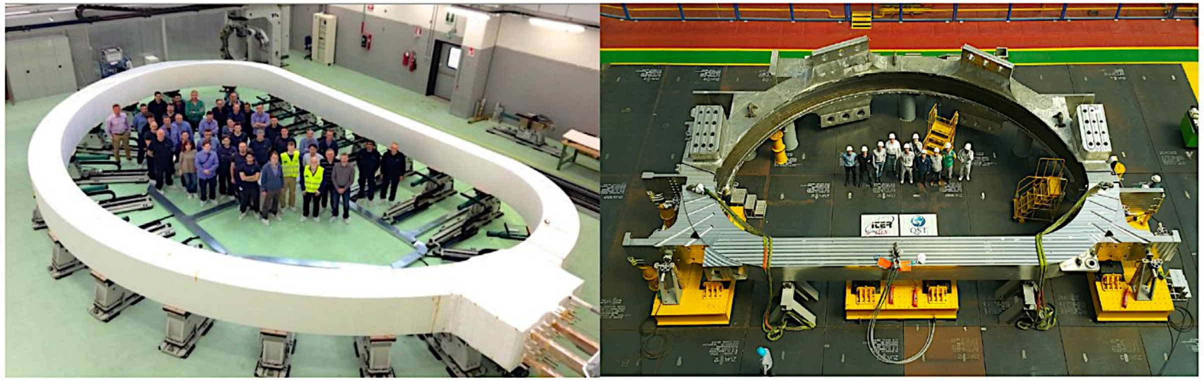
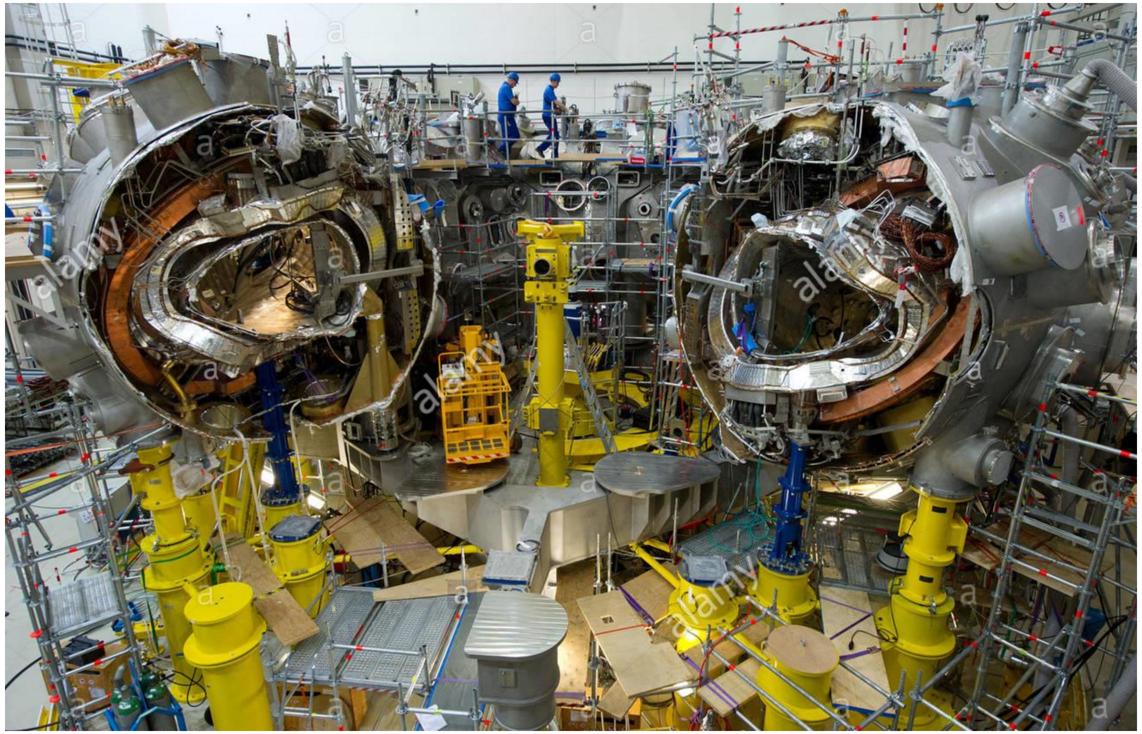


Figure 3. (left) First TF winding pack ready for insertion into the case; (right) first TF case ready for winding pack insertion.

Figure 4. (left) Fabrication proceeding on the first CS module; (right) PF6 sixth double pancake resin impregnated.

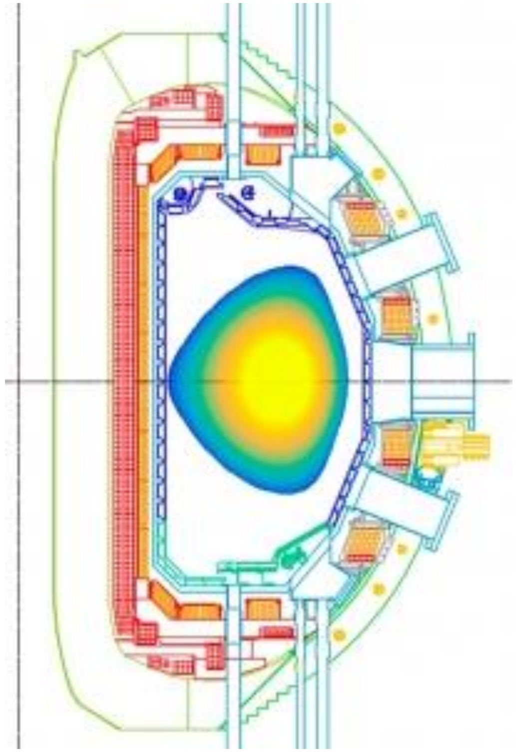
ITER

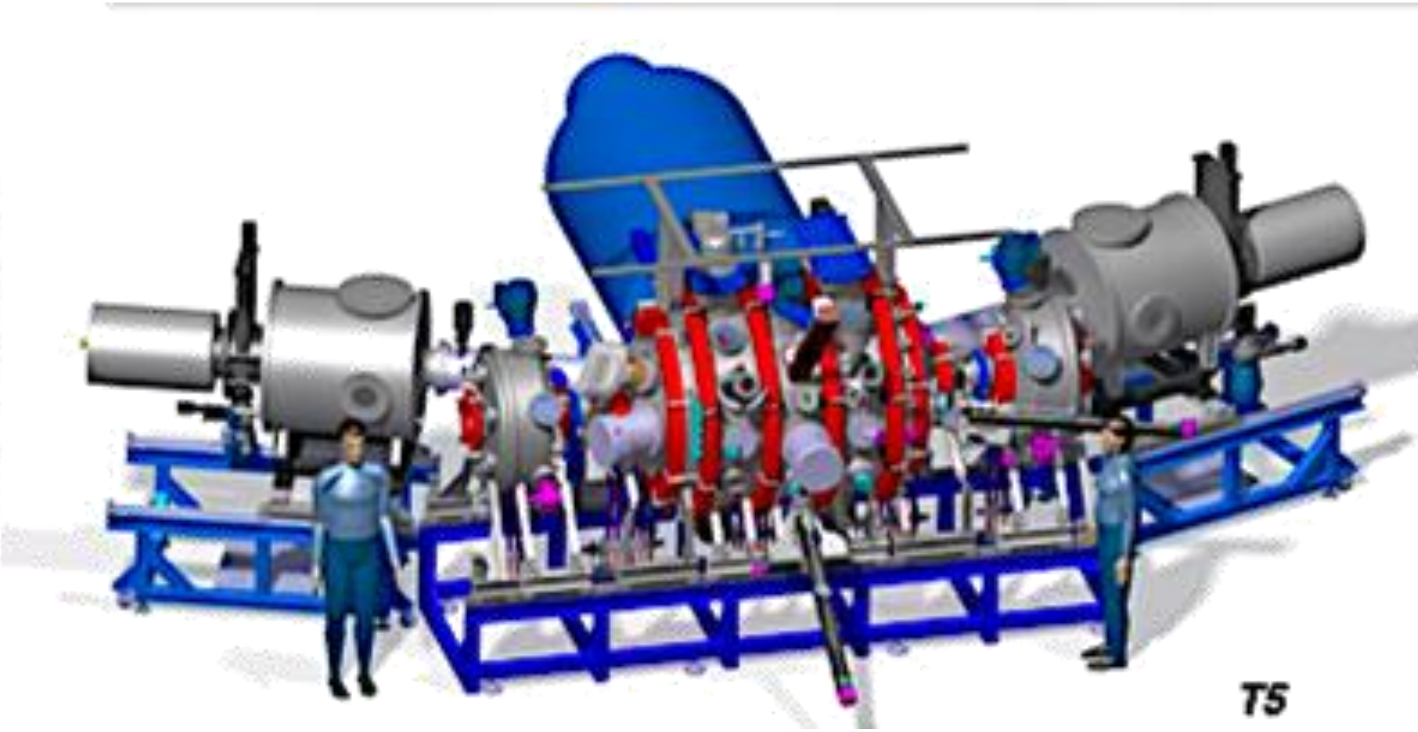
JET



Wendelstein 7-X

Today there are three *privately funded (>100M each)* projects to use REBCO windings for fusion



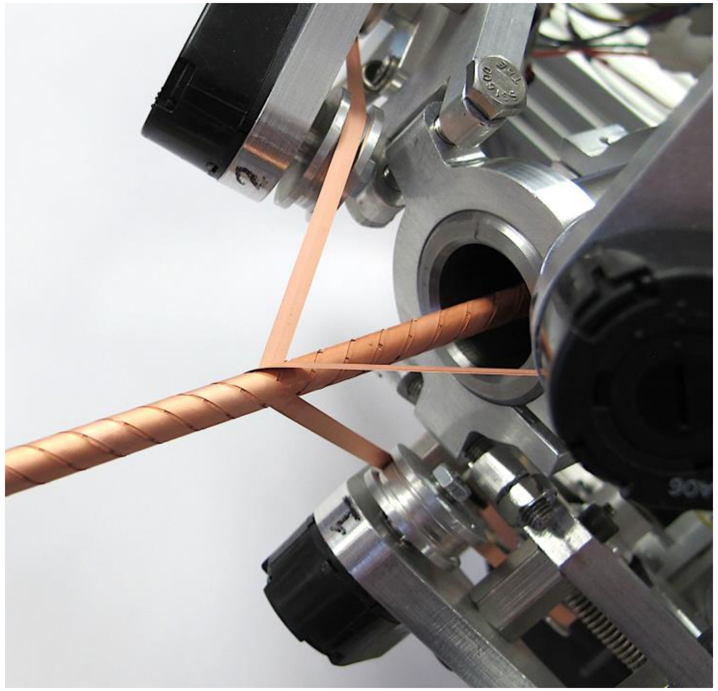


CFS tokamak; **TE tokamak,** **LMA mirror**

Each would require complex windings of high-current cables with cable current ~20 kA – 40 kA

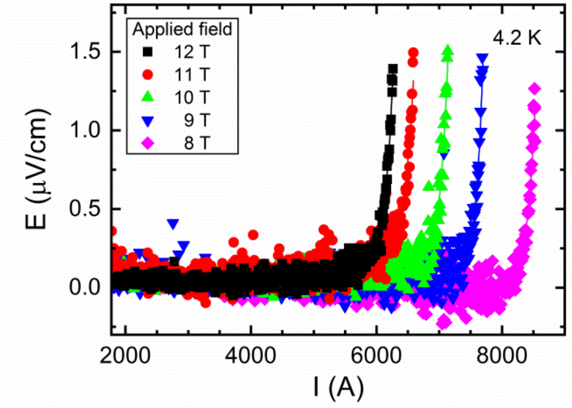
ACT has developed such a REBCO cable that has the potential to meet their requirements

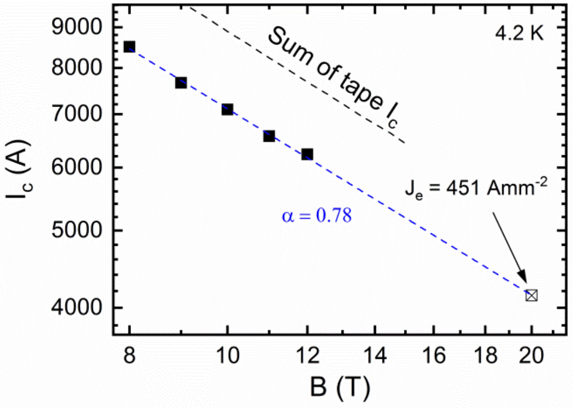
- See ten Kate's talk this morning…



CORC® wire to increase J_e(20 T)

- 32 tapes (2 mm (25 μm) and 3 mm (30 μm) width)
- Outer diameter 3.42 mm
- Average pinning
- 81 % I_c retention





New record J_e (12 T) 678 A/mm^2
Extrapolated J_e (20 T) 451 A/mm^2
I_c(B) closely follows that of the tapes

Danko, ICMC 2019

There's just one problem… REBCO is ruinously expensive!

This has motivated us to develop a cable-in-conduit technology that

- Preserves the full wire current density in a ~30 A cable under the conditions of background field and Lorentz stress in a >16 T winding;
- Can be fabricated using NbTi, Nb_3Sn, and Bi-2212 wires;
- Sub-windings of all three superconductors can be wound and heat-treated separately to yield optimum performance;
- Sub-windings can be assembled and preloaded into as *hybrid windings* in toroid and solenoid geometries while preserving wire performance;
- Windings can be spliced to NbTi interconnect cables with ~nΩ resistance, and splices can be de-mounted and remounted.
- High-modulus armor can be co-wound with the CIC to support large radial and hoop stress in >16 T windings.

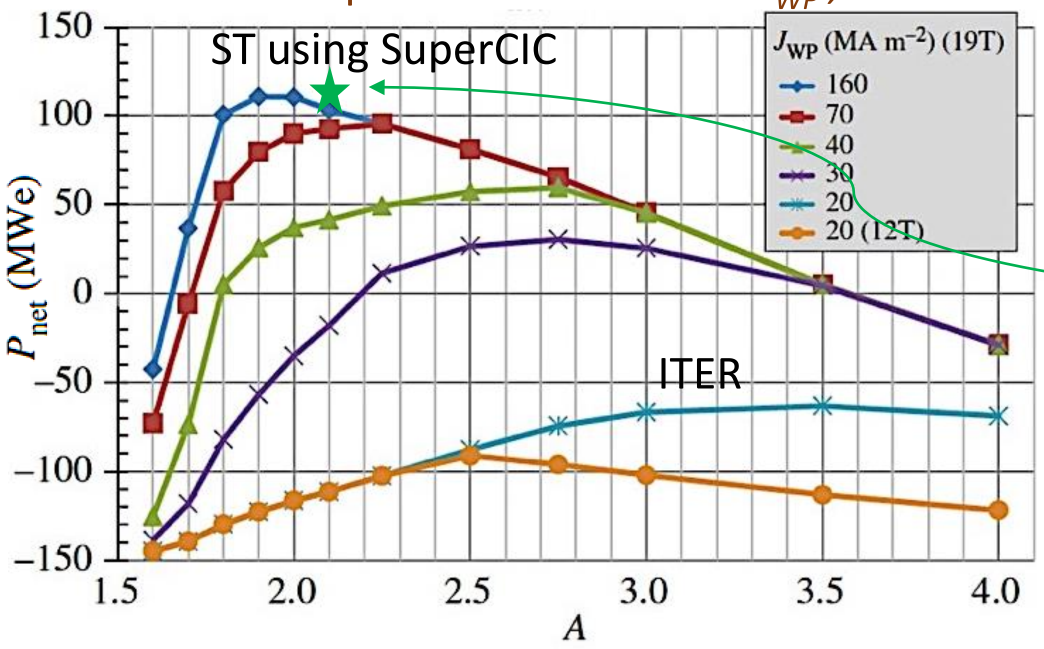
Accelerator Technology Corp. and Texas A&M are developing a SuperCIC technology that can accomplish all of those goals.

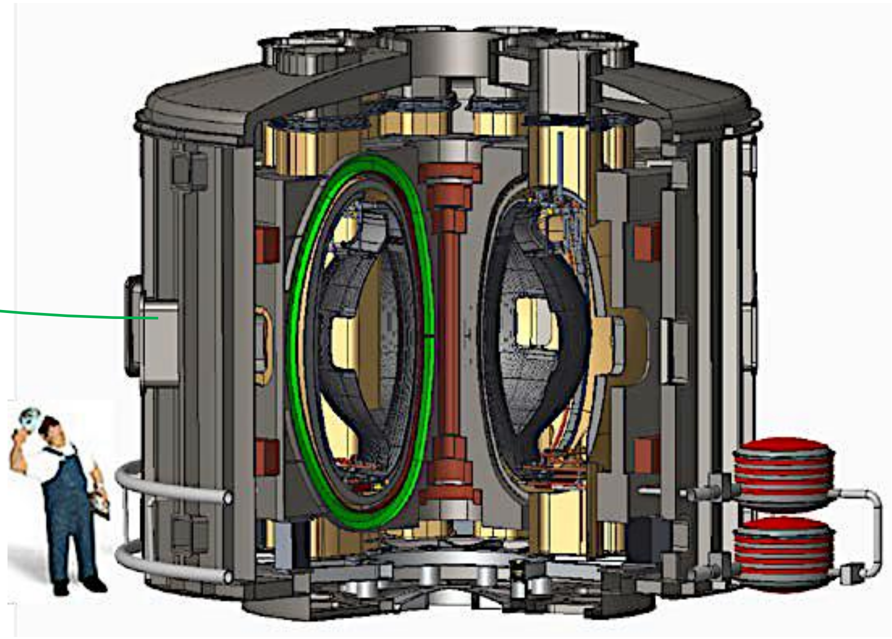
Context for fusion magnetics

Menard evaluated the importance of the current density J_{WP} in the winding package and the toroid aspect ratio A as performance parameters for the particular case of tokamak configurations.

https://royalsocietypublishing.org/doi/full/10.1098/rsta.2017.0440?af=R

Net electric power as function of J_{WP} , A

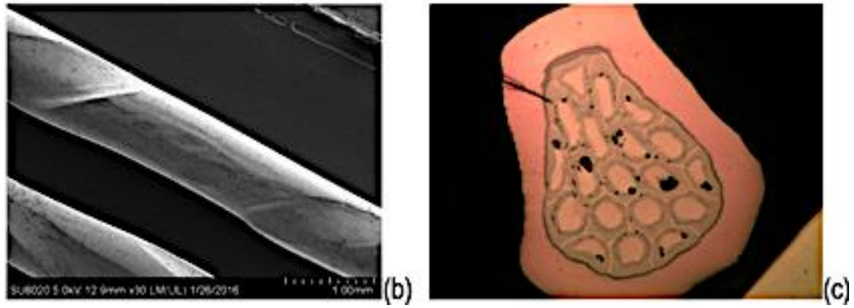




PPL's design for a Spherical Tokamak

The current density J_{WP} in the conventional CIC used in fusion magnet magnets arises from damage to the wires.

wire bundle within an ITER TX cable



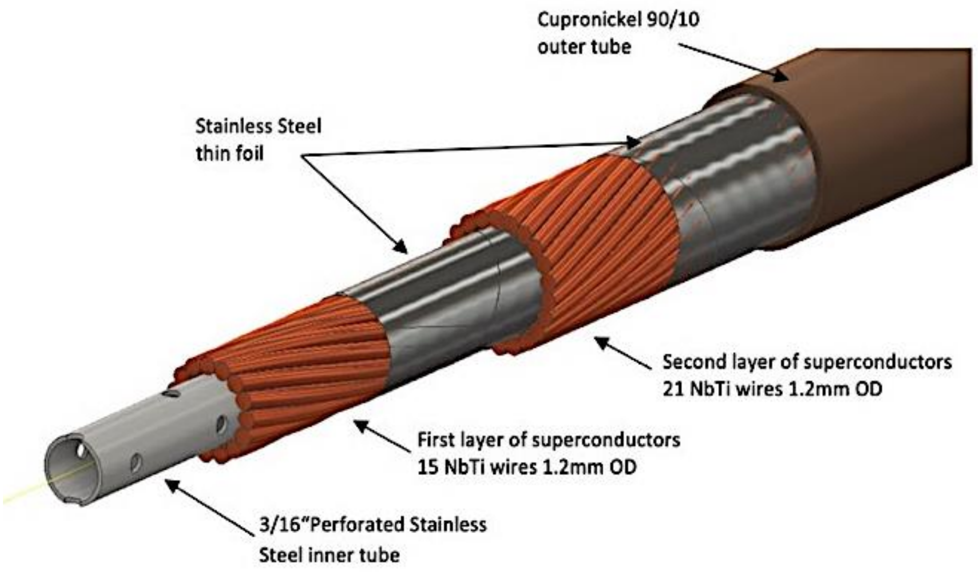
J_{WP} = 20 for ITER CIC

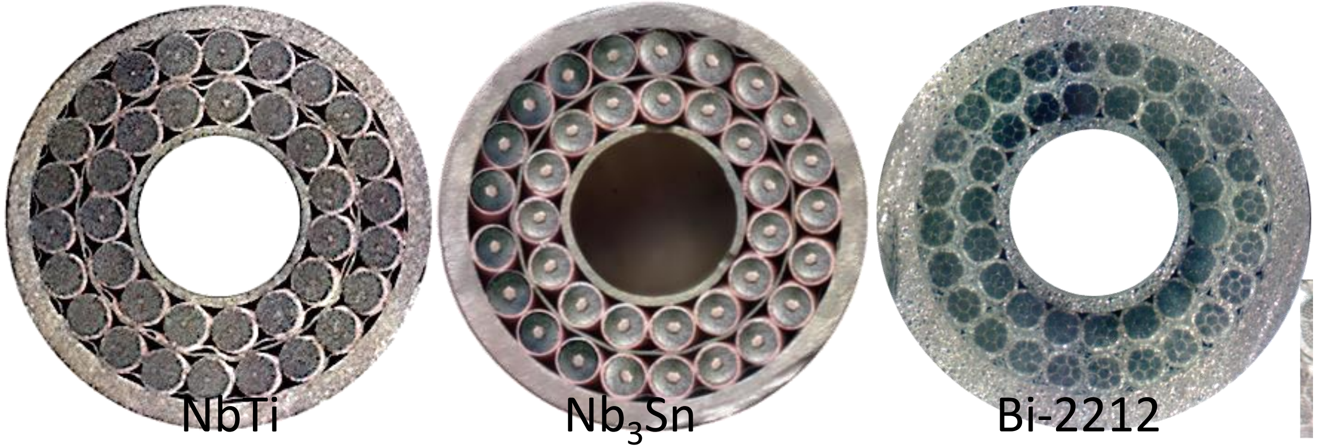
extracted wires from the cable, showing indentations where wires are compacted against one another; c) cross-section showing damaged microstructure

Qin *et al.*, Superconduct. Sci. and Tech. **30**, 115012 (2017)

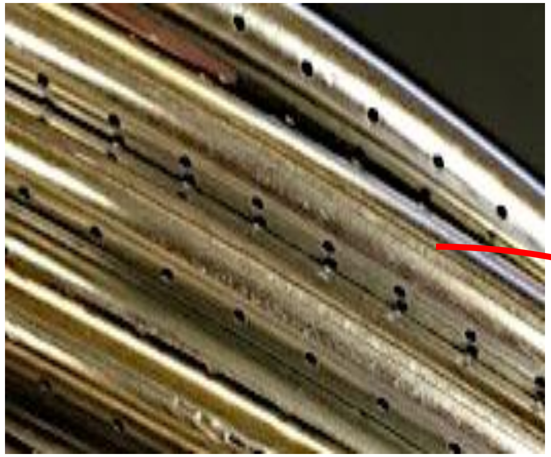
Super-CIC:

Support all wires within the cable and protect them from all exterior stress, so that they maintain the full wire performance in the cable and in the winding.

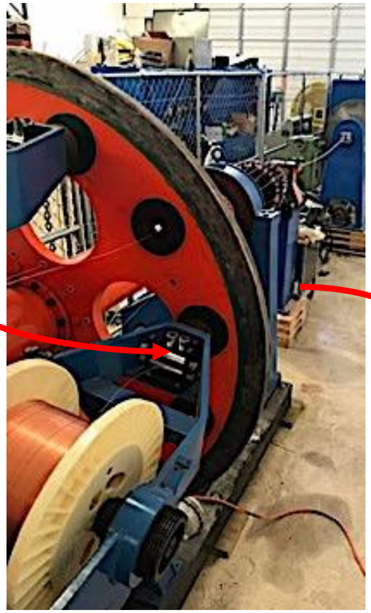




Fabrication of SuperCIC:



perforated center tube



cable superconducting wires onto center tube

apply foil over-wrap;

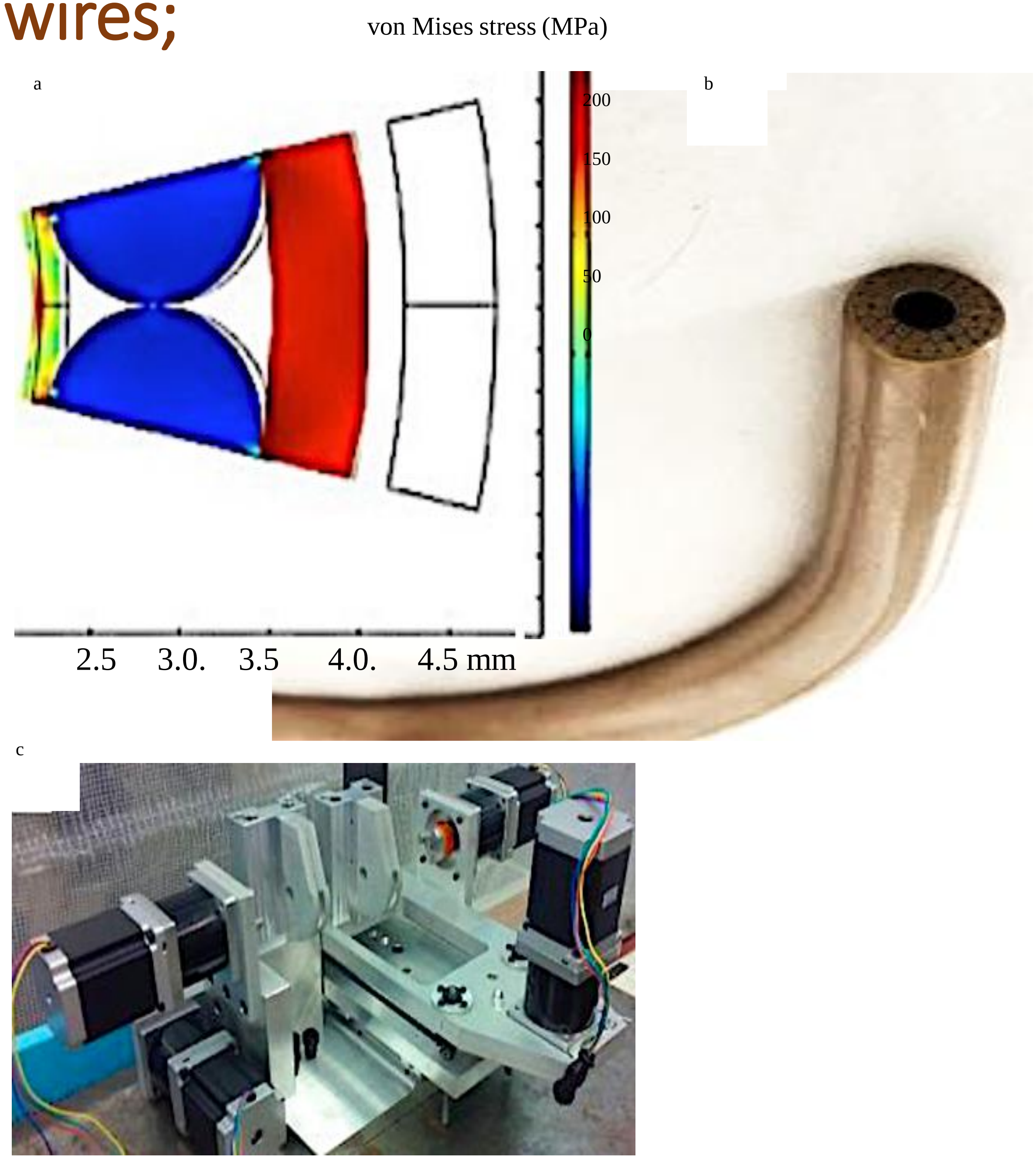
pull straight 150 m cable through sheath tube with loose fit

draw sheath tube onto cable.

ATC now manufactures 2-layer SuperCIC in lengths up to 150 m as a manufactured product.

Draw sheath onto cable to immobilize wires; spring-load them against center tube; stress management at cable level.

Form small-radius bends using robotic bender.
No damage to filaments in wires,
Preserve wire performance in CIC.

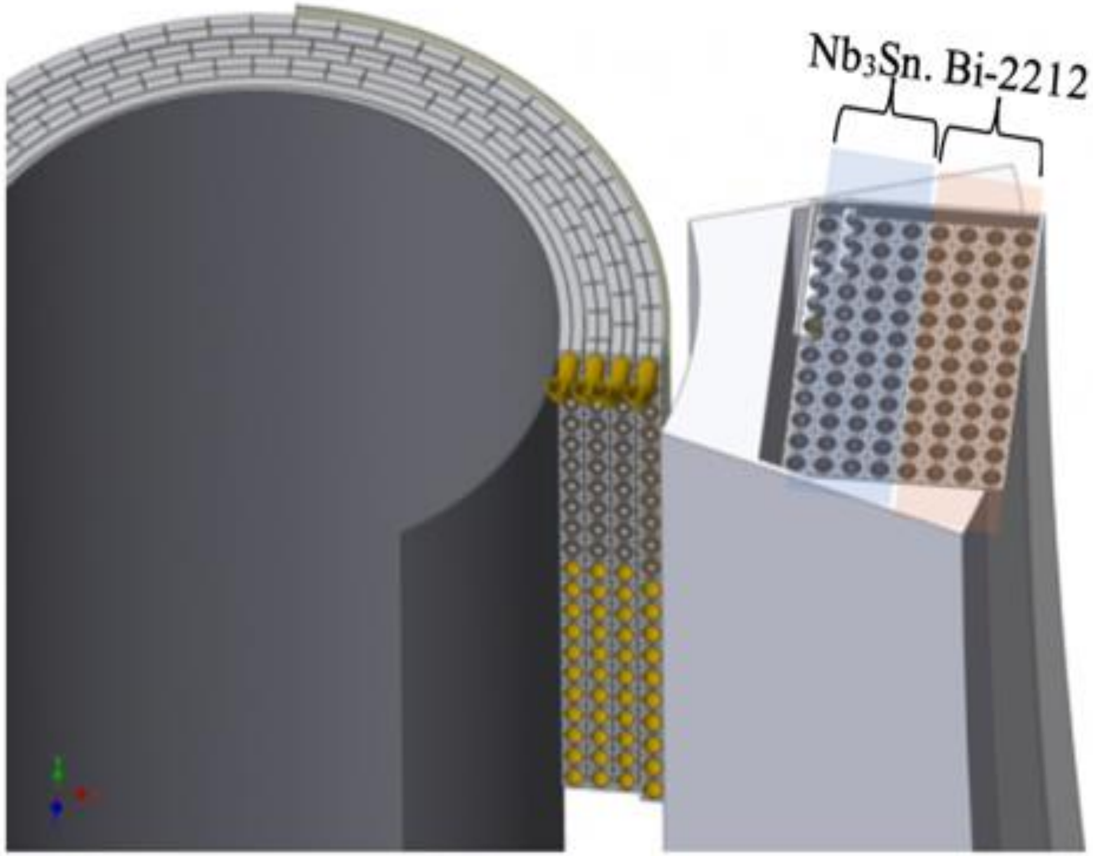


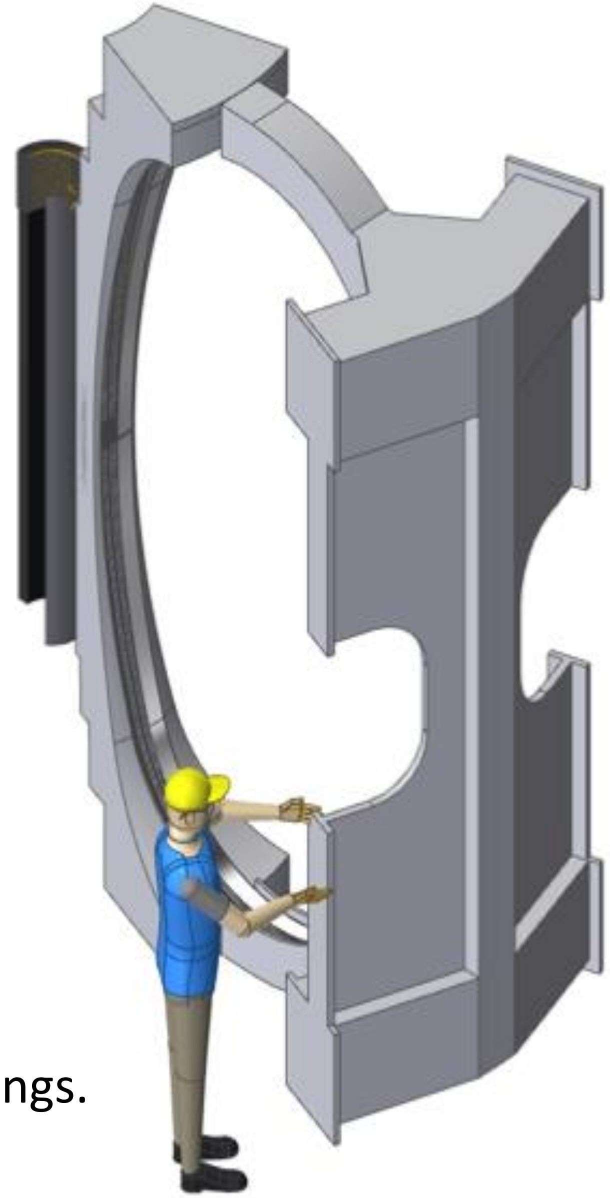
Co-wound armor to provide robust high-modulus support for radial and hoop stress

Two half-shells of armor are co-wound with SuperCIC

configuration for coil-winding co-wound armored SuperCIC for a solenoid winding.

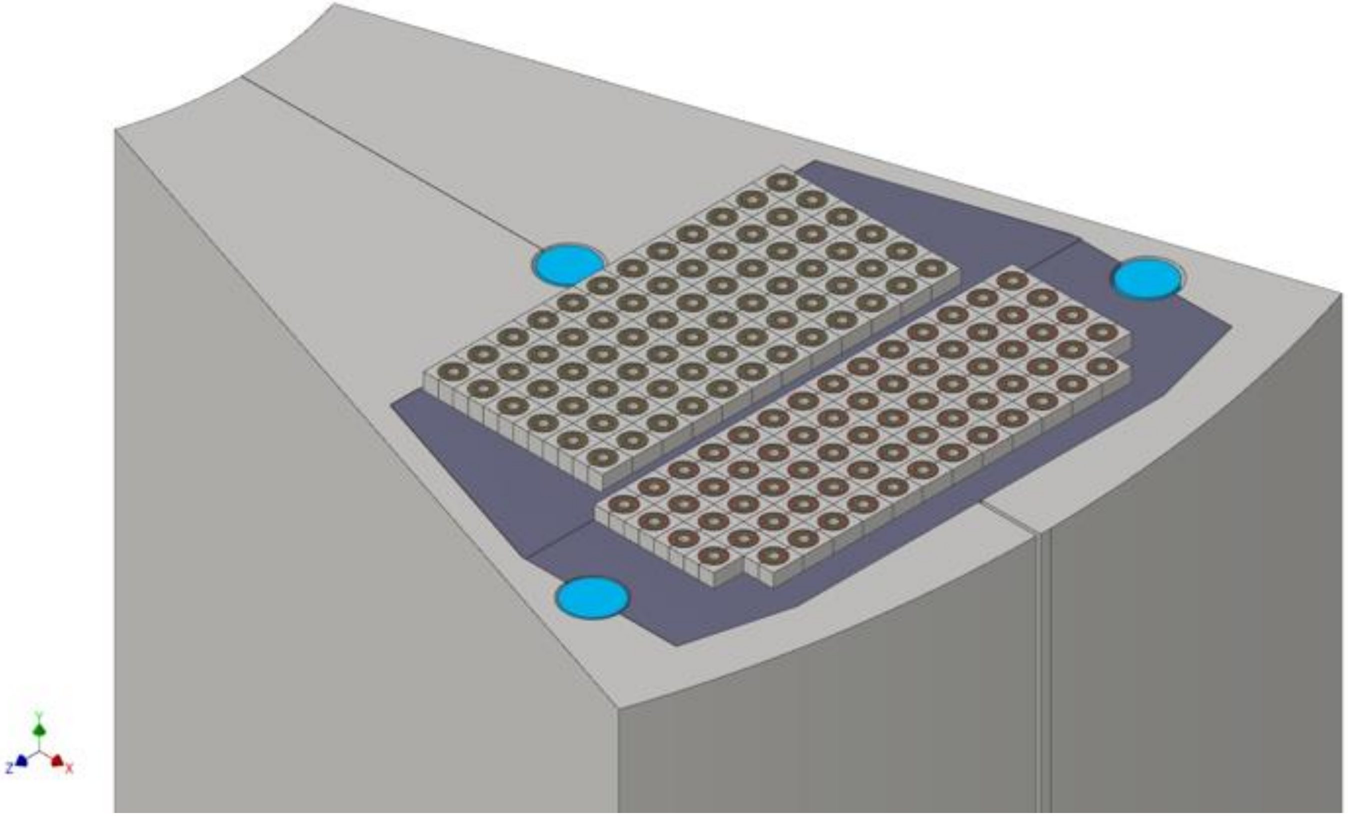
Hybrid windings using SuperCIC for a spherical tokamak





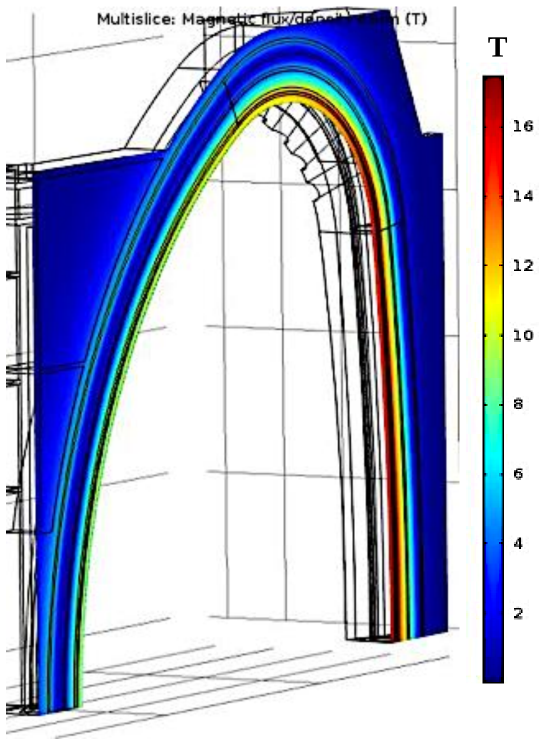
The division of sub-windings follows naturally the decreasing field-at-conductor.
Hybrid windings can be used to minimize the expensive superconductor in the windings.

Payoff: 16 T hybrid-coil toroid with J_{WP} = 140 A/m^2
Spherical tokamak with A = 2.0



R_0	1.2	M
B @R_0	6.7	T
B @coil	17.4	T
A	2.0	
CIC	# strands, wire dia.	
Bi-2212	42 strands, 0.97 mm	
Nb_3Sn	42 strands, 0.97 mm	
NbTi		
J_{WP}	140	MA/m^2
I_{op}	28.7	kA
I_{op}/I_c @4.2K	0.7	
# layers	11	
SC(Layers)	Bi-2212 – 5 layers	
	Nb_3Sn – 6 layers	
Quantity of SC	Bi-2212 - 2.25	Ton
	Nb_3Sn - 1.9	Ton
Cost of SC	Bi-2212 - $31M	
	Nb_3Sn - $ 3M	
	$34 M	

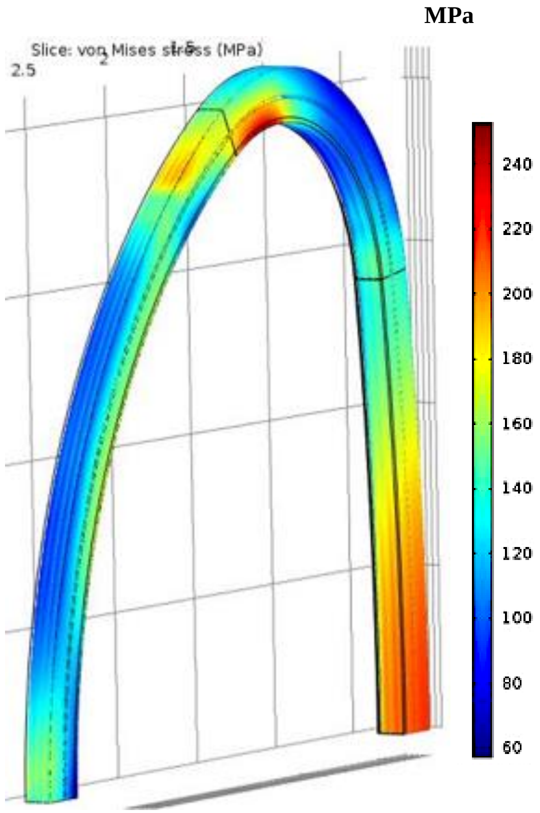
Magnetic field in the windings:

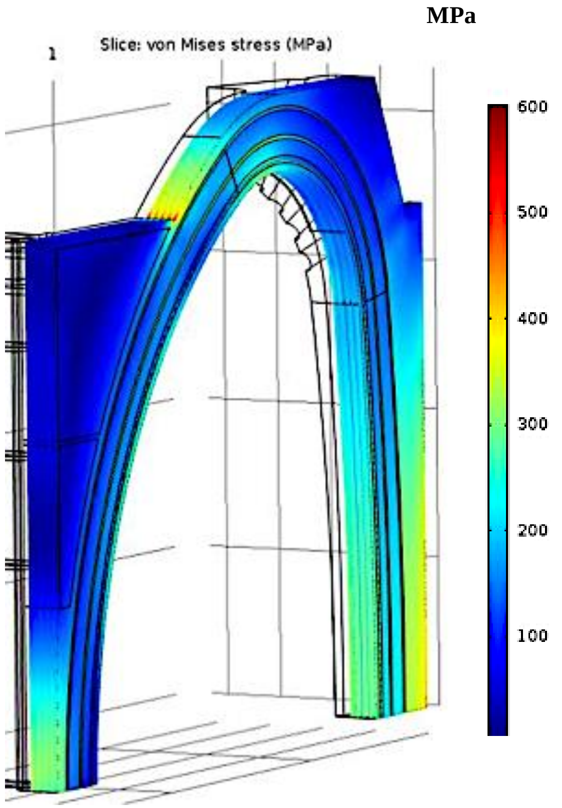


Stress management in windings:

Winding package;
Stress in armor < 250 MPa

Stress in SuperCIC < 120 MPa





Structural support:
Stress < 600 MPa

Conclusions

SuperCIC windings brings several innovations to high-field magnetics for fusion systems:

• The SuperCIC manages stress at the cable level, so the huge accumulated Lorentz forces within windings cannot degrade fragile filaments of high-field superconductors. Round-profile SuperCIC makes it possible to integrate the cylindrical sheath and high-strength support elements as separate ingredients.

• The SuperCIC windings can be formed with small radius of curvature without harm to the wire or cable. It therefore provides a basis for high-field, small-radius solenoids, flexibility in reducing the aspect ratio of toroid windings, and challenging configurations for poloidal windings.

• SuperCIC supports hybrid coil strategies, in which sub-windings of different high-field conductors can be separately fabricated and heat-treated and then assembled as a winding.

• SuperCIC with Bi-2212 can be fabricated with provisions for sheath tube and over-wrap metals for which the sheath tube can serve as the pressure retort for over-pressure processing (no high-pressure retort).

• SuperCIC can be co-wound with a 2-piece armor shell that provides robust management of radial and hoop stress.

• Cryogen flow within SuperCIC distributes cooling throughout the volume of the winding, so that the variation in winding temperature from non-uniform heat loads is suppressed.

TAMU and ATC are collaborating with PPPL to develop conceptual designs utilizing SuperCIC for the solenoid and toroid windings of their spherical tokamak.