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# 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

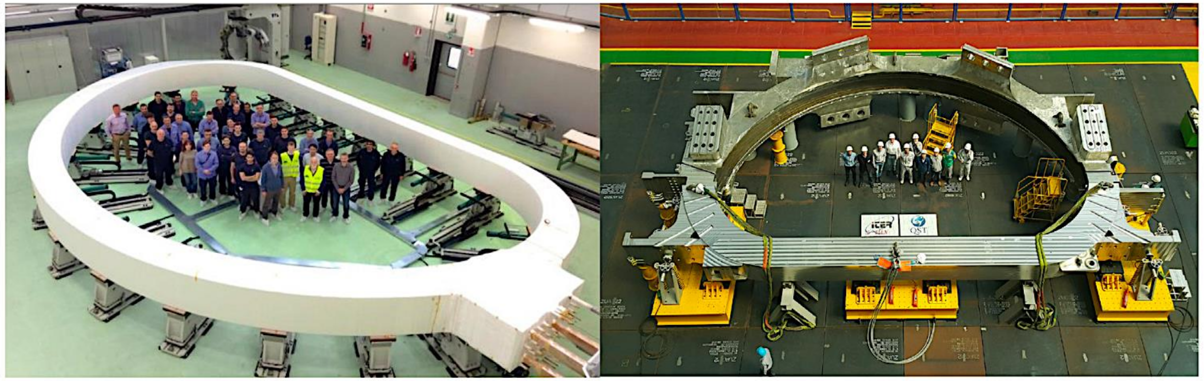
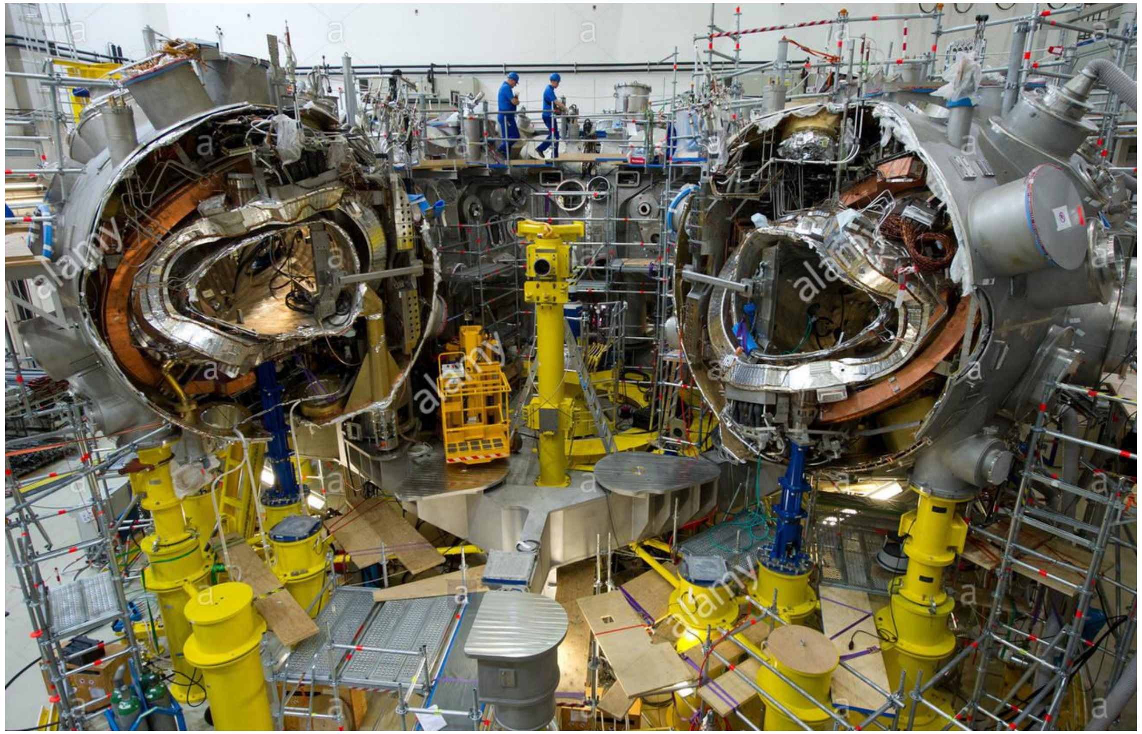


**Figure 3.** (left) First TF winding pack ready for insertion into the case; (right) first TF case ready for winding pack insertion.

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

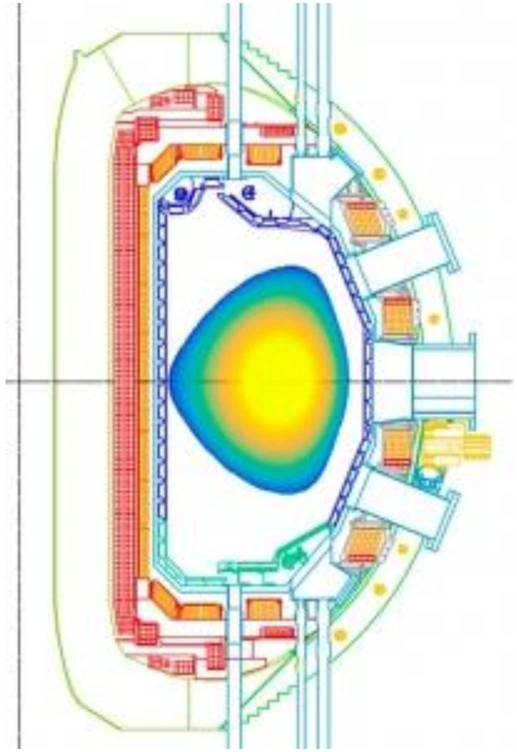
**ITER**

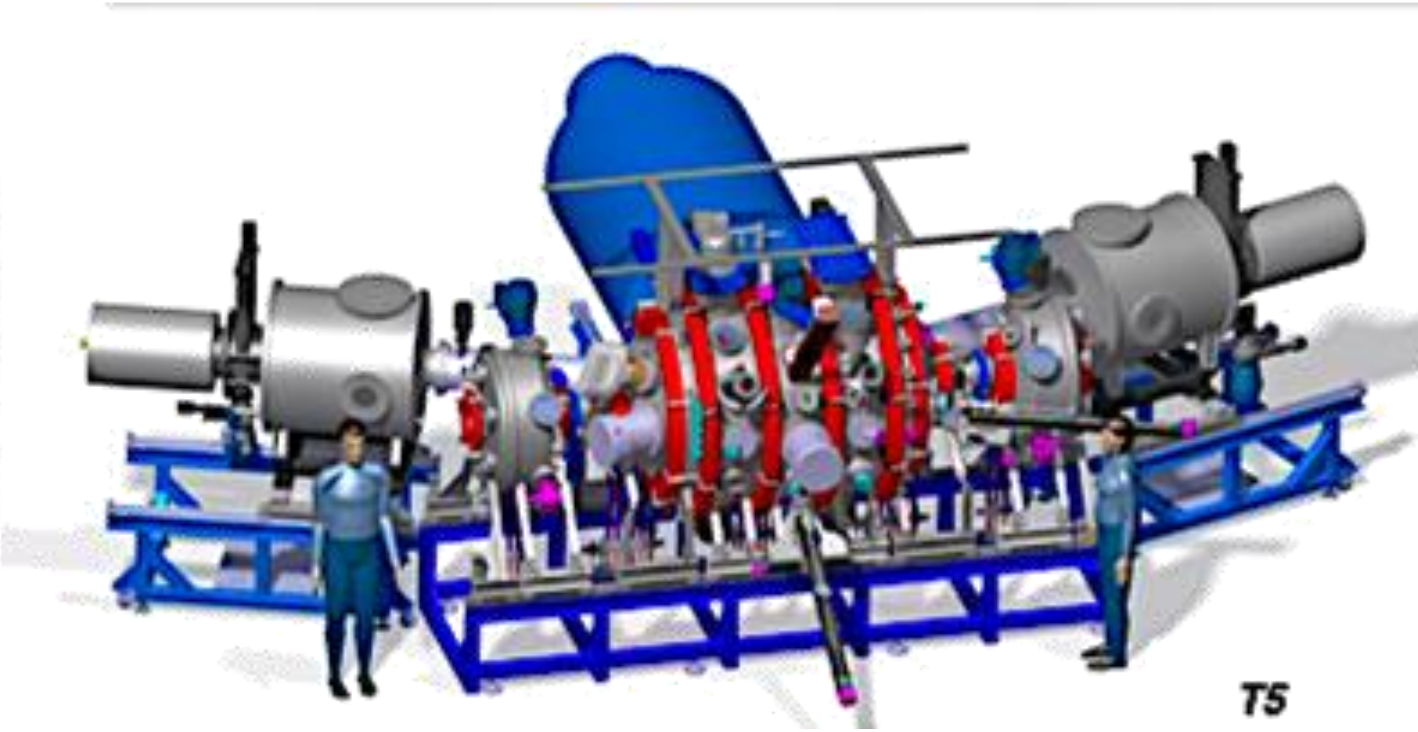
**JET**



**Wendelstein 7-X**

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



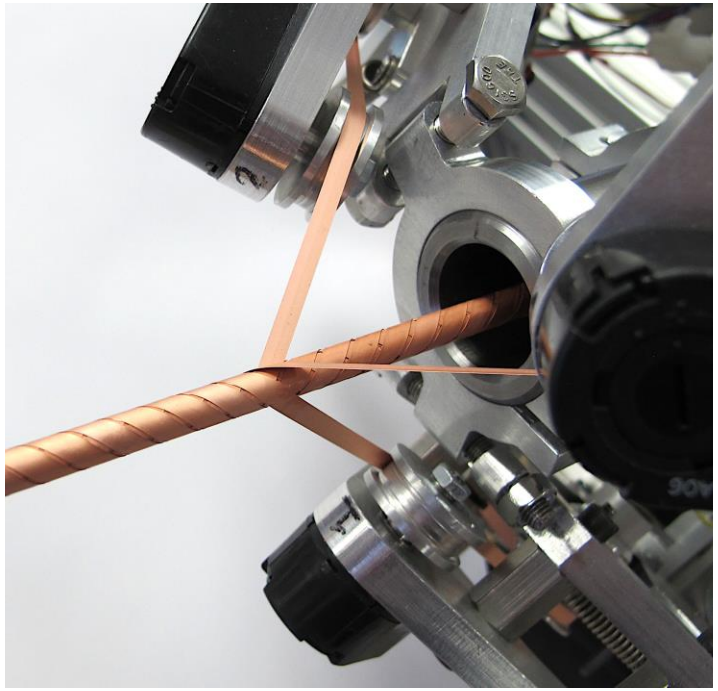



**CFS tokamak; TE tokamak, LMA mirror**

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

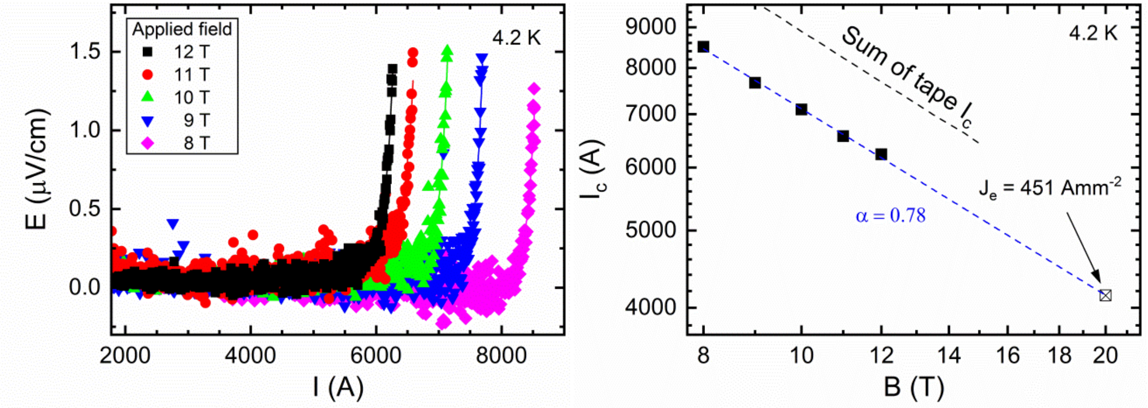
# ACT has developed such a REBCO cable that has the potential to meet their requirements

- 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 ~n$\Omega$ 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.

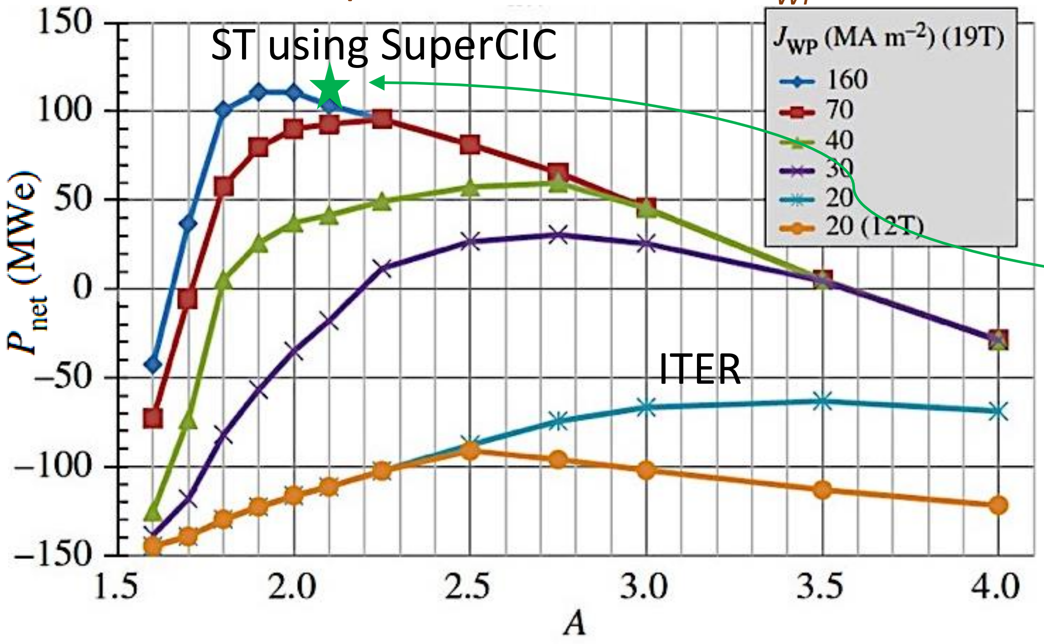
**Accelerator Technology Corp. and Texas A&M are developing a SuperCIC technology that can accomplish all of those goals.**

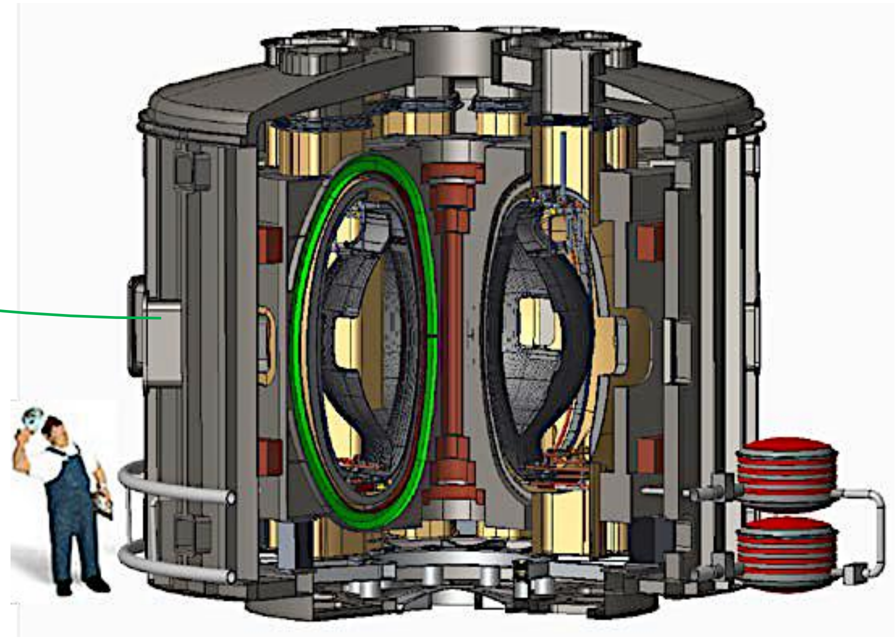
# Context for fusion magnetics

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 $J_{WP}$ , $A$



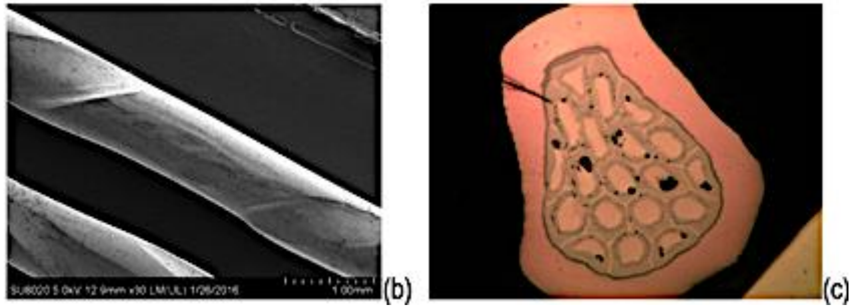



PPL's design for a Spherical Tokamak

# 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

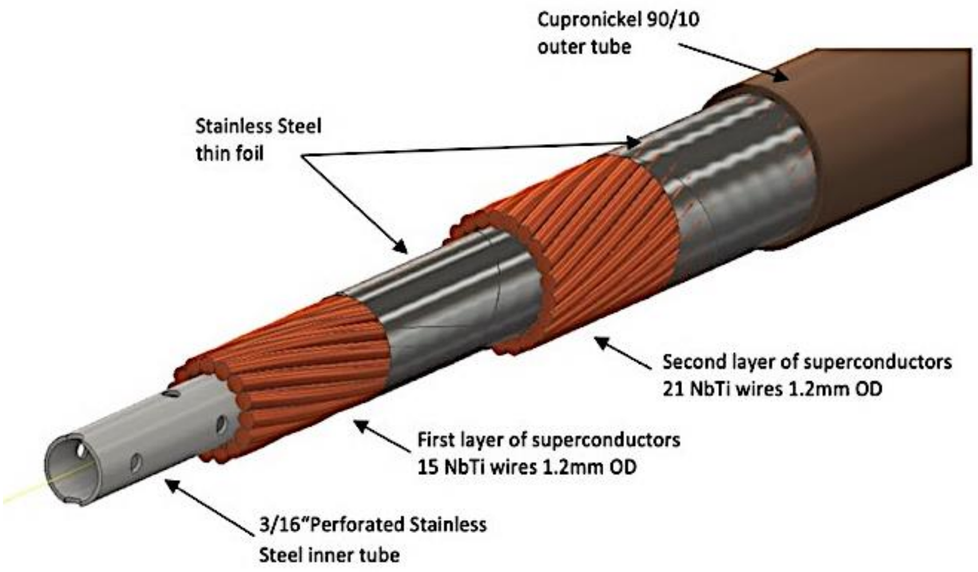


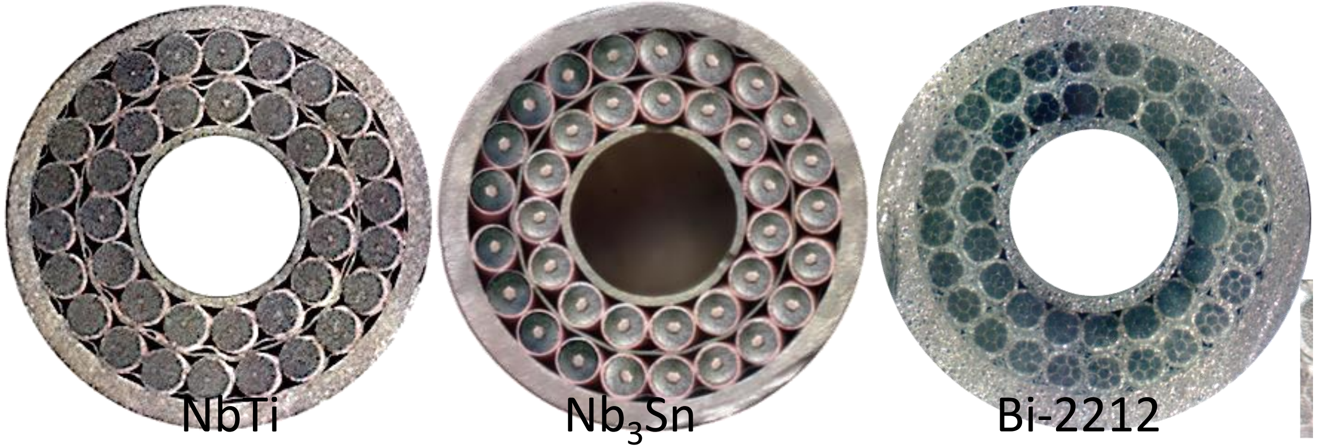

extracted wires from the cable, showing indentations where wires are compacted against one another; c) cross-section showing damaged microstructure

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

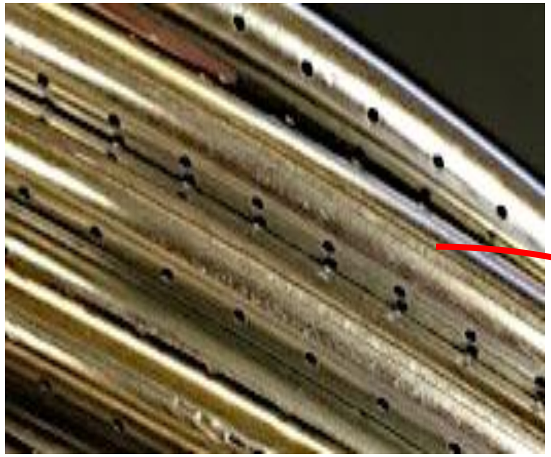
# Super-CIC:

## 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.

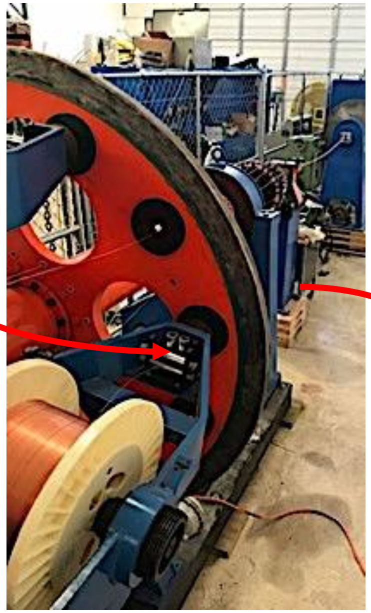


# Fabrication of SuperCIC:



perforated center tube



cable superconducting wires onto center tube

apply foil over-wrap;

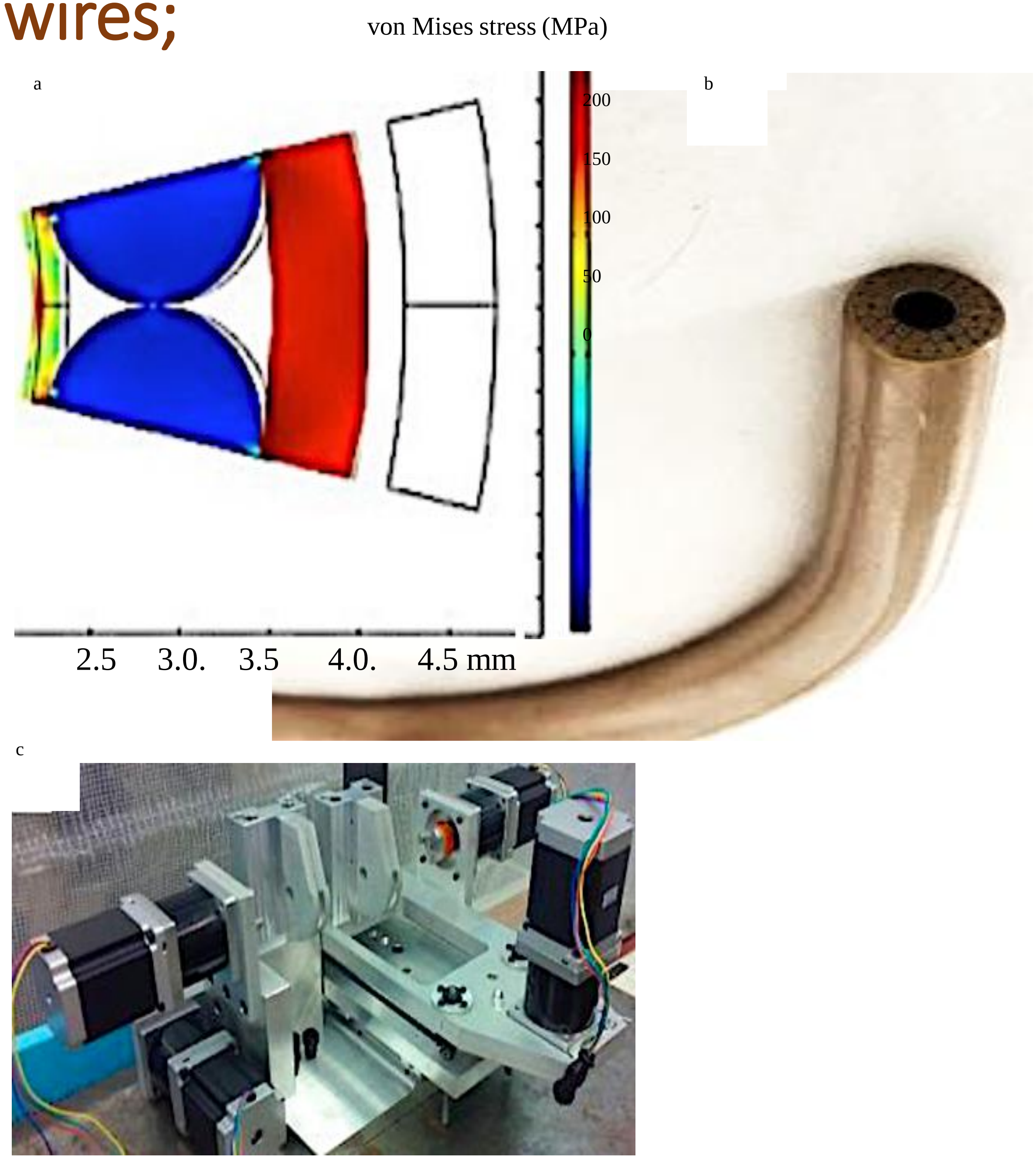
pull straight 150 m cable through sheath tube with loose fit

draw sheath tube onto cable.

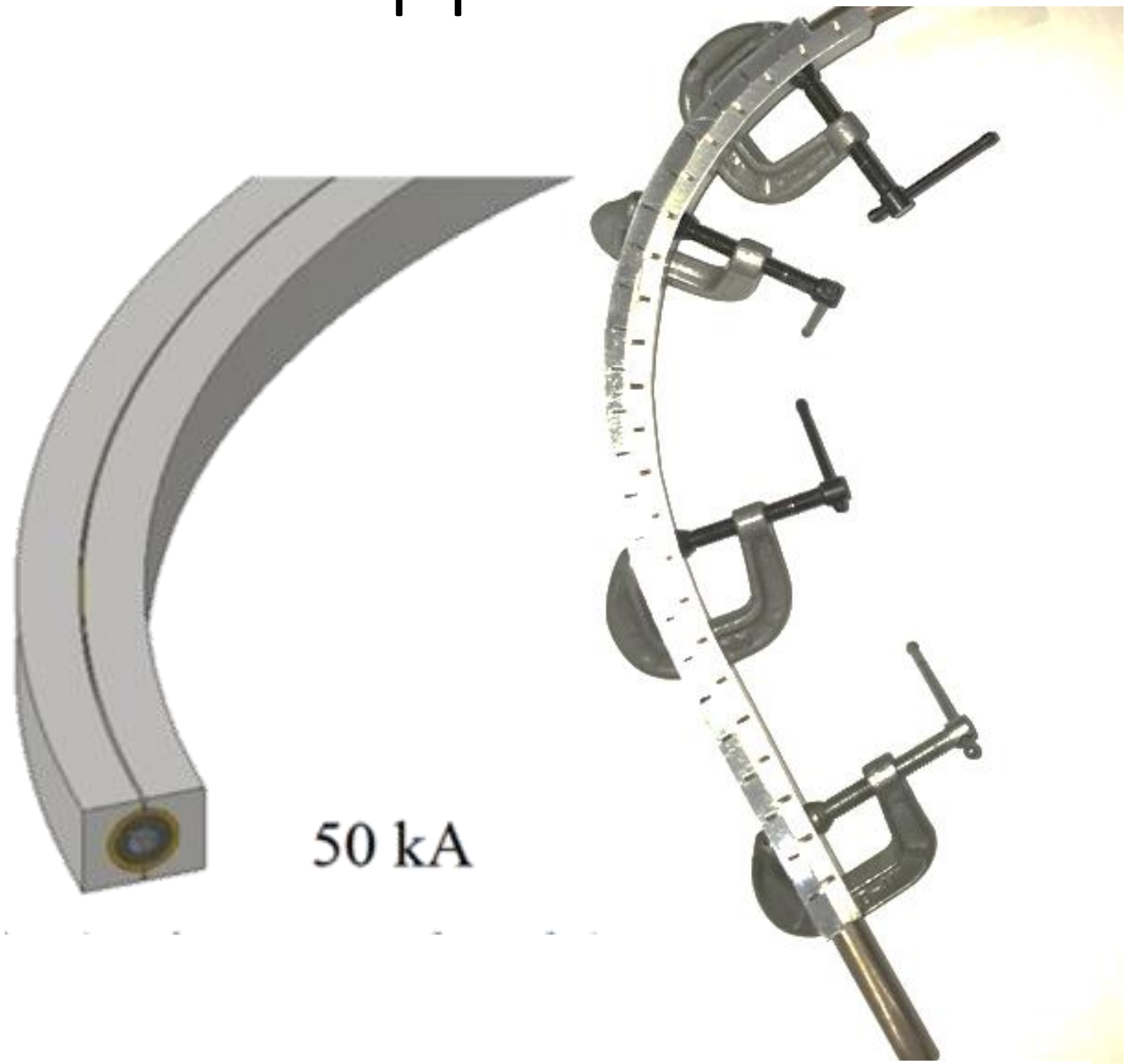
ATC now manufactures 2-layer SuperCIC in lengths up to 150 m as a manufactured product.

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.



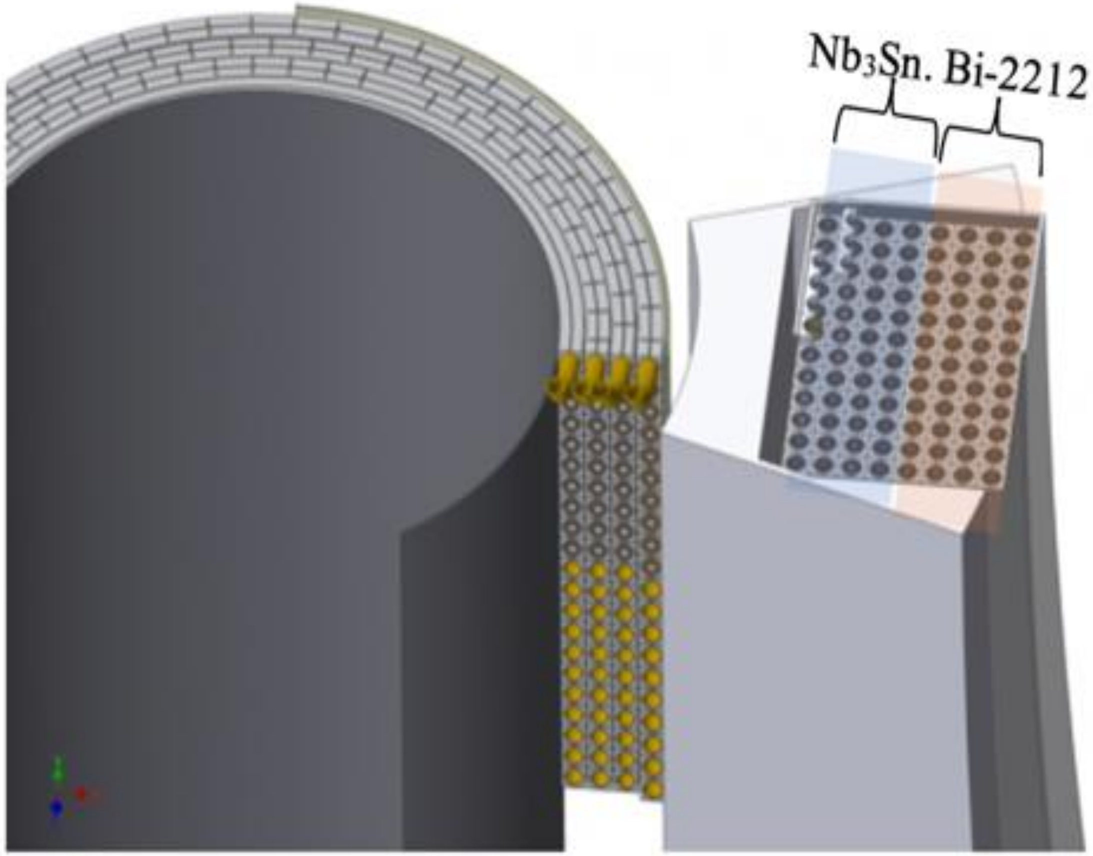
# Co-wound armor to provide robust high-modulus support for radial and hoop stress

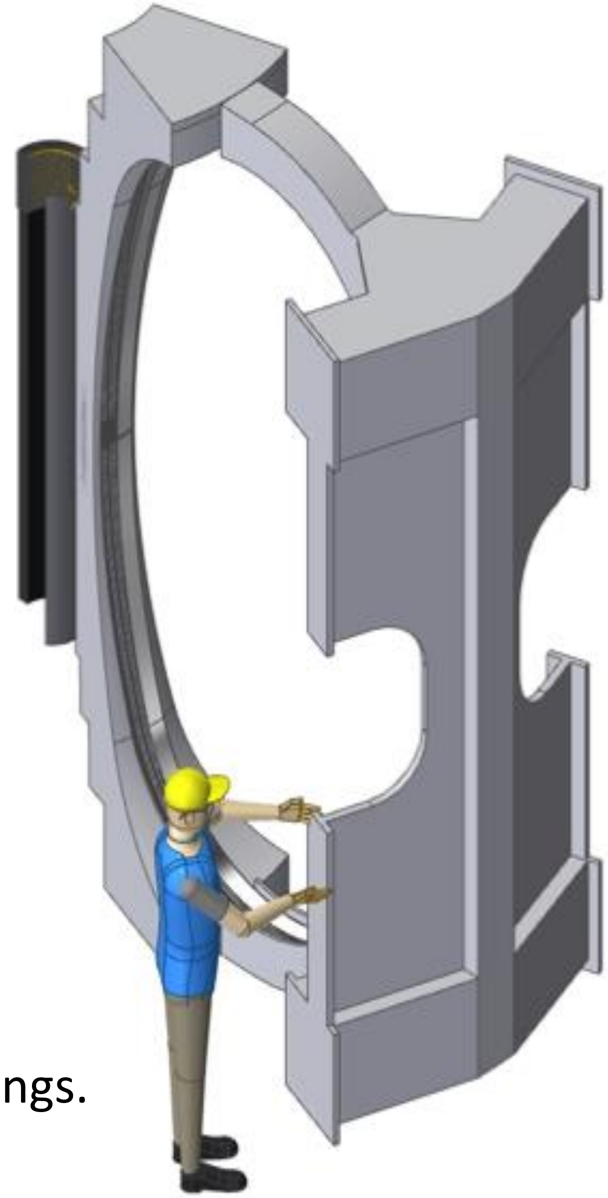



Two half-shells of armor are co-wound with SuperCIC

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

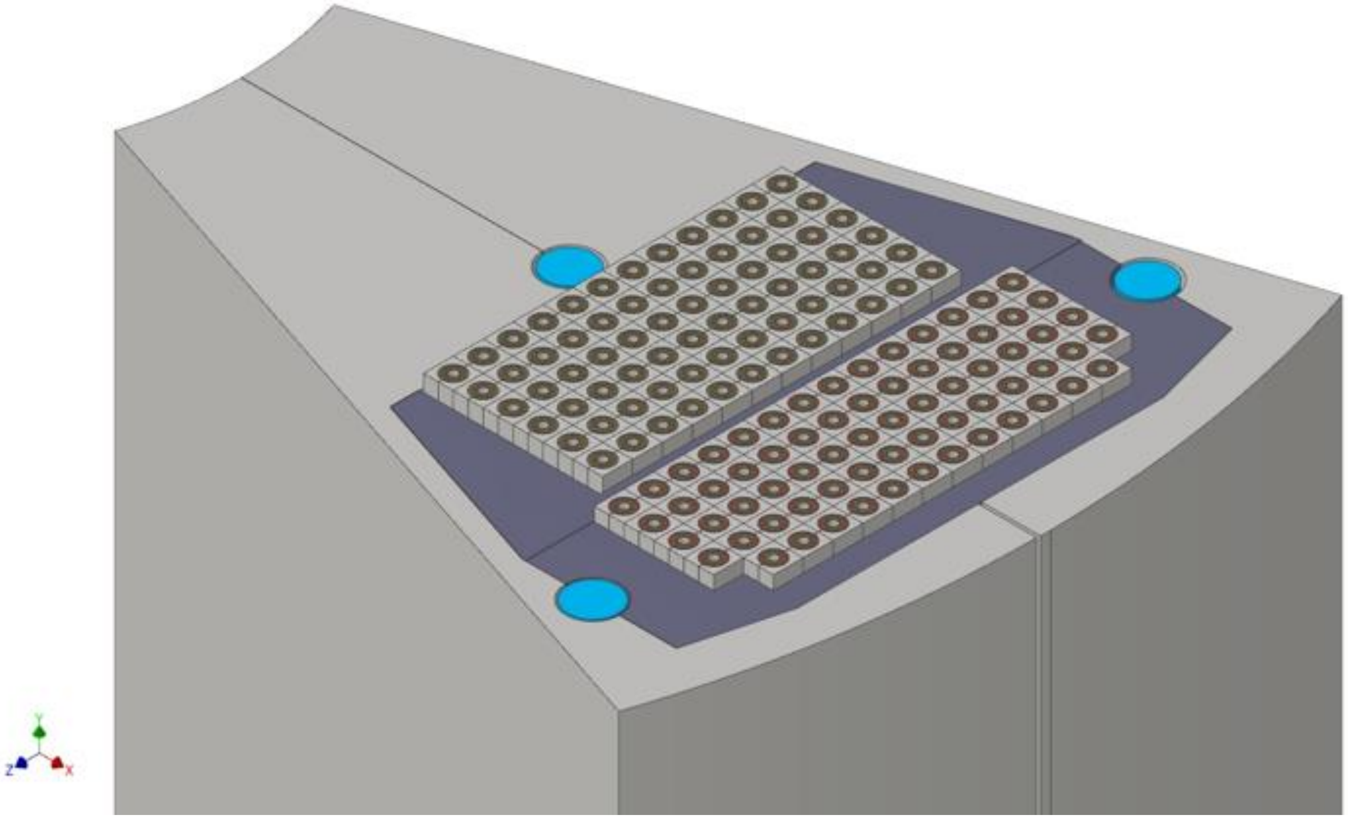
# Hybrid windings using SuperCIC for a spherical tokamak



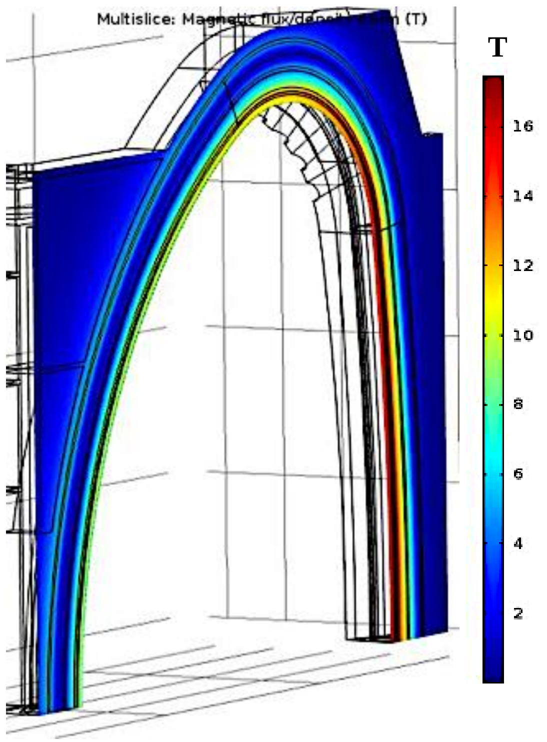
The division of sub-windings follows naturally the decreasing field-at-conductor.
Hybrid windings can be used to minimize the expensive superconductor in the windings.

# 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 | |

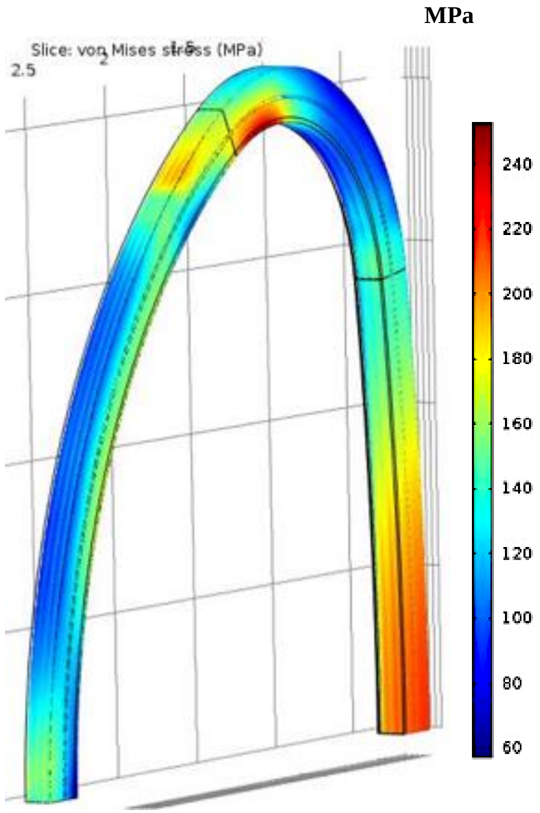
# Magnetic field in the windings:

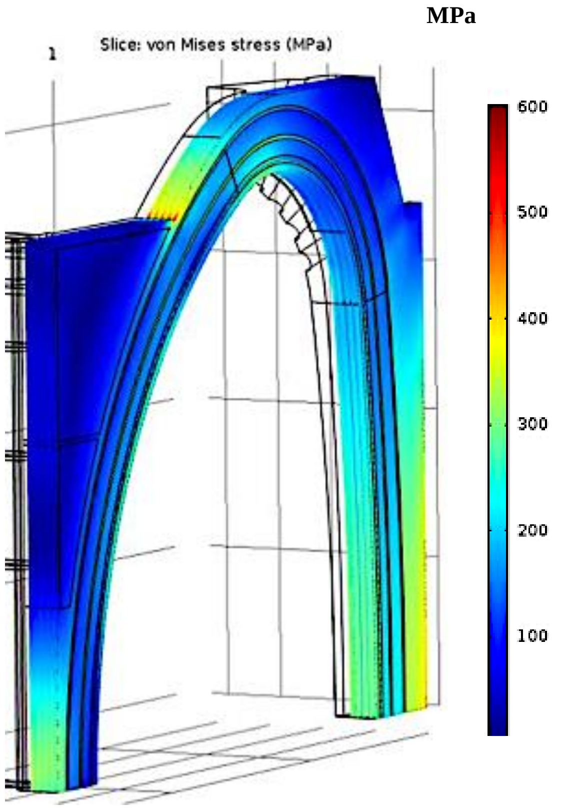



# Stress management in windings:

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.**