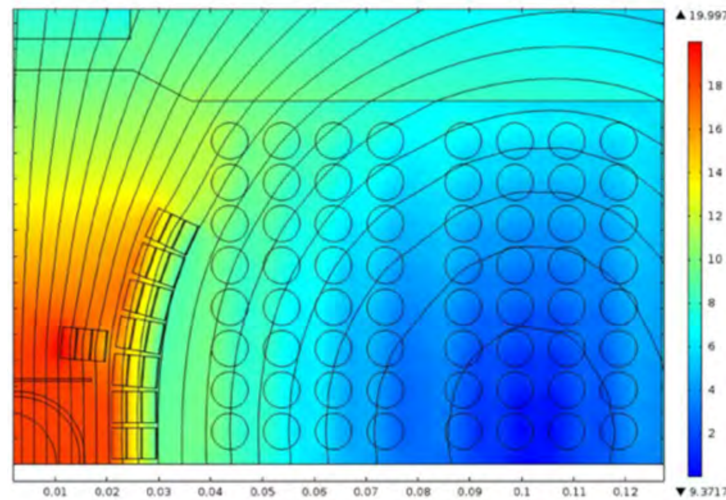
Wire, Cable, and Magnet R&D at Texas A&M and ATC

Textured-powder Bi-2212 with LAR ~ 1:1 (SBIR DE-SC0021688)

Nb_3Sn cable-in-conduit (SBIR DE-SC0021688)



Conformal REBCO winding for 18 T dipole

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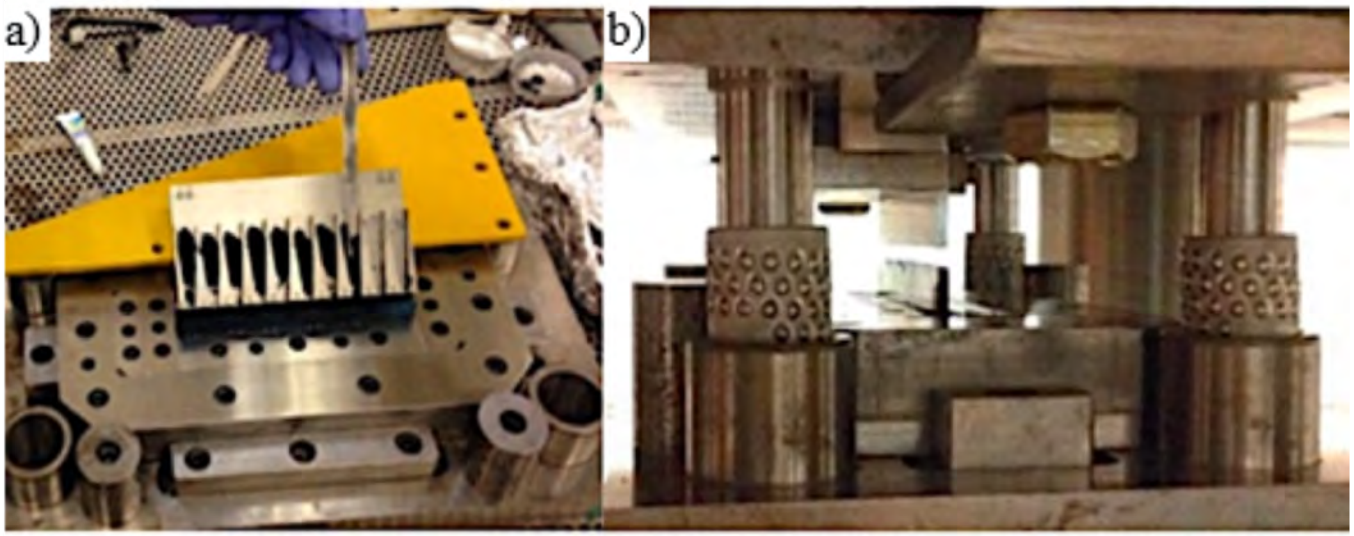
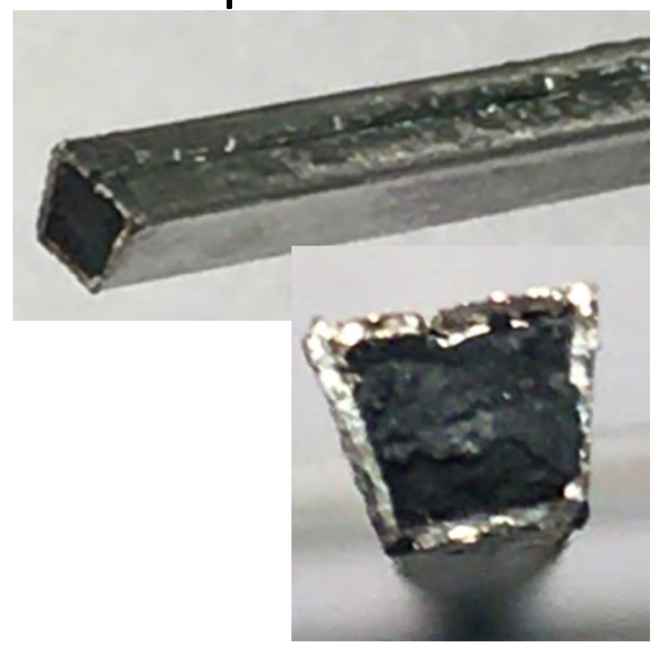
Textured-powder Bi-2212

- We are developing a new method to fabricate Bi-2212/Ag wire using textured-powder cores – funded by **SBIR DE-SC0021688.**
- The objective is to reduce the LAR of Ag in multi-filament wire from 3:1 for OPIT to 1:1, to reduce cost while retaining wire performance.
- Bi-2212 fine powder is loaded with a Ag wrap and compressed to form a *textured-powder (TP) bar:*

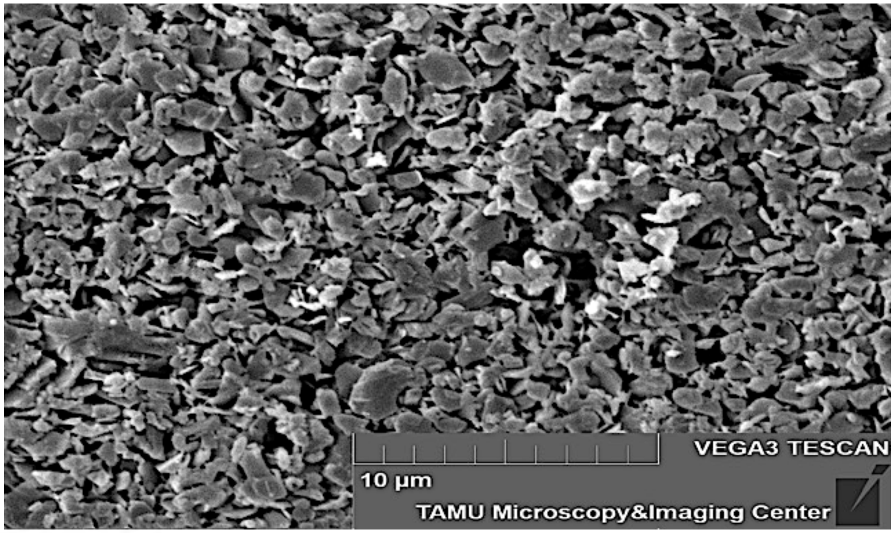




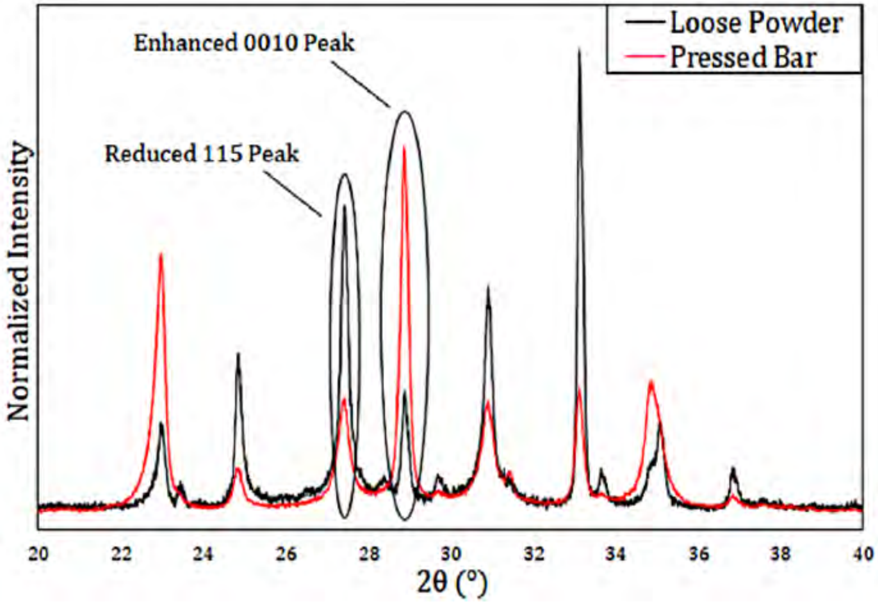
- The TP bars are then assembled into a symmetric multi-filament billet.
- The billet is extruded and drawn to fine-wire.

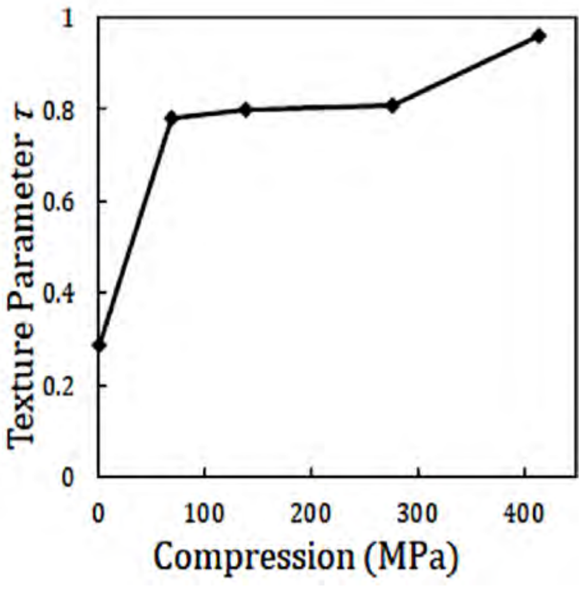
Bi-2212 is micaceous

- Each grain in Bi-2212 fine powder has a plate-like morphology in which its c-axis thickness is 50x less than its a-b dimensions:



- The powder particles align face-on to the direction of compression, so it is feasible to produce a high texturing among the powder particles:
- Texture factor: $$\tau = \frac{I(0010) - 0.25I(115)}{I(0010) + 0.75I(115)}$$
- XRD:





TP Bi-2212 has low shear modulus in the a-b plane

- As with mica, a textured powder of Bi-2212 flows with low modulus under shear in the a-b plane.
- Our objective is to achieve a flow modulus under extrusion and drawing that is comparable to Ag, so that the bars in a billet will reduce conformally.
- *Assemble a symmetric array of TP:*
  - *Use tetrahedral bars*, and chose # bars and bar size in each layer so that all bars have ~same cross-section area.
  - Bar forming: The cavity in the female die is lined with a 50 mm Ag foil strip cladding. The top flaps of silver foil are folded over.
  - The foil-clad bar is uniaxially compressed to 200 MPa. The silver provides a slip-plane between the powder and the walls of the die. After compression, the TP bar releases readily from the die and is nearly hermetically sealed on its side surfaces.

Single-layer billet experiments

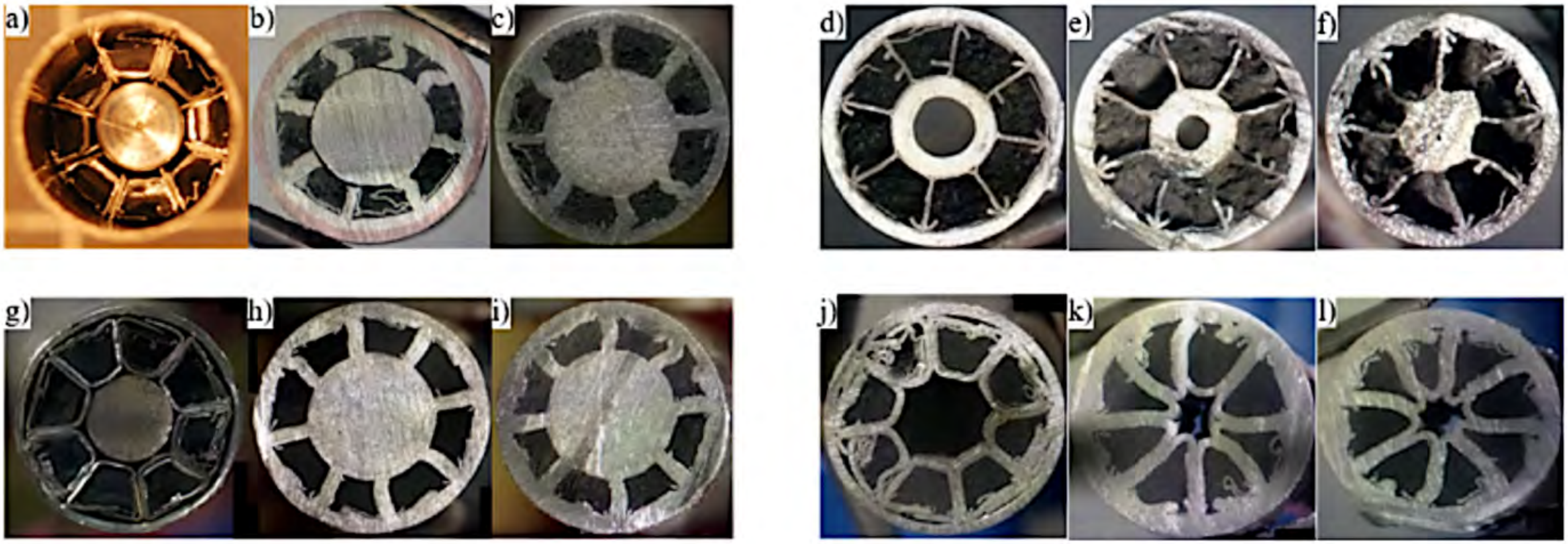


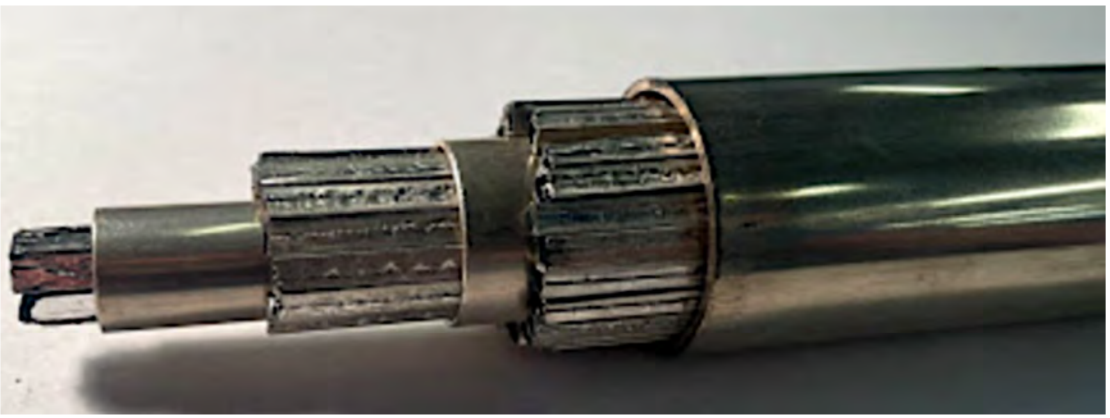
Fig. 5. Cross-sections of tail samples taken from each billet as it was drawn to successively smaller diameter:

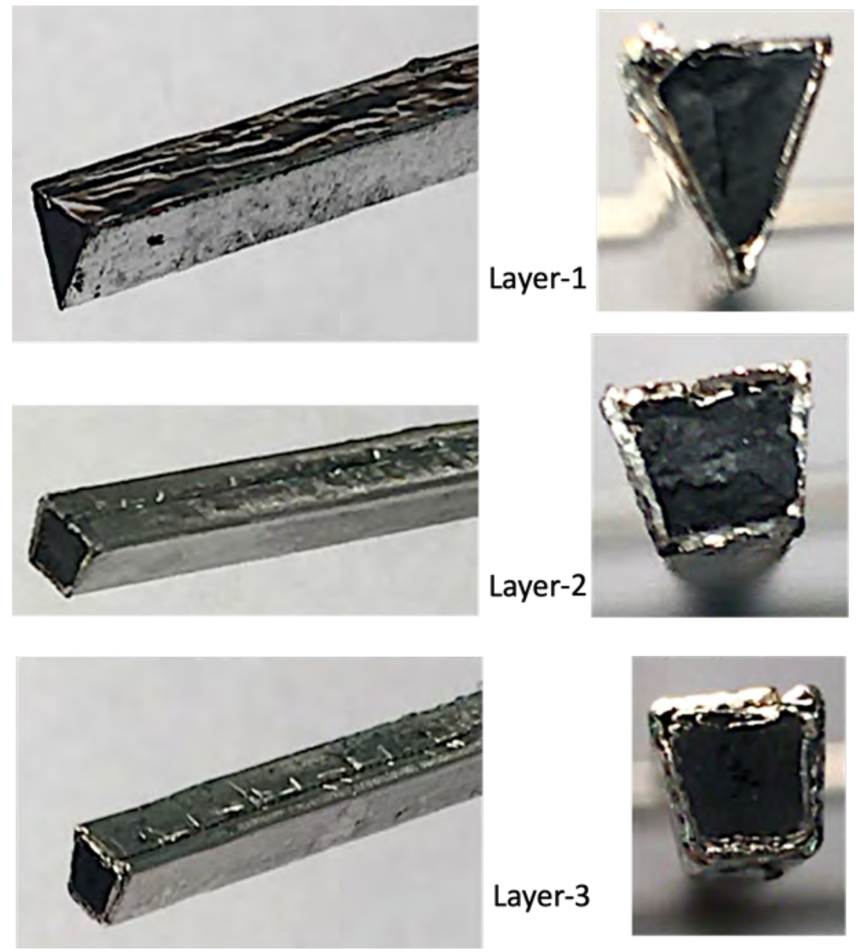
Billet 1	50 μm clad, 400 μm spacers, sold core	a) 12.70 mm OD, 3.42 LAR	b) 7.98 mm OD, 1.84 LAR	c) 6.20 mm OD, 1.69 LAR
Billet 2	100 μm clad, no spacers, tube core	d) 8.40 mm OD, 1.17 LAR	e) 6.20 mm OD, 1.06 LAR	f) 4.06 mm OD, 1.07 LAR
Billet 3	50 μm clad, 200 μm wrap, solid core	g) 12.70 mm OD, 2.32 LAR	h) 9.60 mm OD, 2.40 LAR	i) 6.76 mm OD, 2.49 LAR
Billet 4	50 μm clad, 200 μm wrap, hollow core	j) 12.40 mm OD, 1.98 LAR	k) 9.80 mm OD, 1.85 LAR	l) 9.30 mm OD, 1.73 LAR

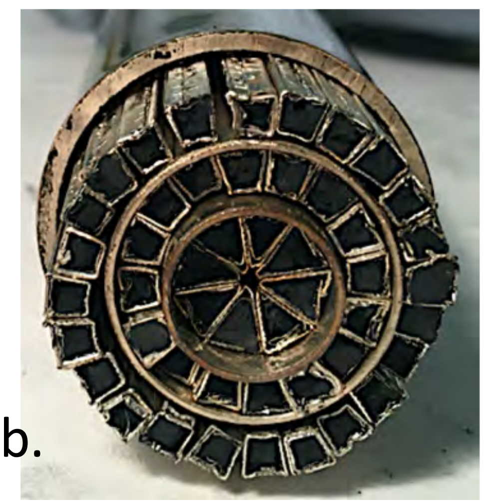
- Experimental billets were made using solid core, tube core, no core.
- *With a hollow tube core*, the Bi-2212 bars drew down conformally with the Ag-alloy sheath tube wrappings – *the LAR was preserved.*
- This result demonstrates that the plastic deformation modulus of the TP Bi-2212 bars is close to that of the Ag structure – a key condition for stable extrusion and drawing.
- But the core remained a challenge – when the hole disappeared, the solid core reduced more slowly than the bars.

Use triangular bars in the core

A solid core does not reduce with the bars; an empty core de-stabilizes the bars so that they deform; a hollow tube core works well until the hole is fllled during drawing, then becomes a solid core.
So we fabricated a *triangular bar* for the core that provides the ~same mix of Bi-2212 and Ag in the core and in the layers:







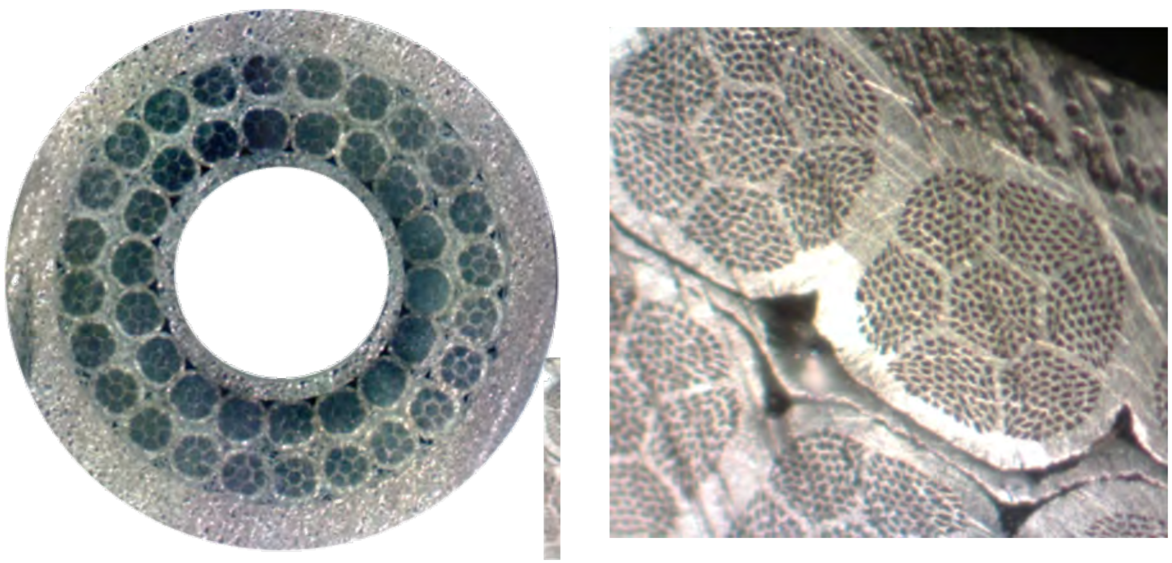
This is a work in progress.
Billets are being drawn at TAMU, extruded at Ames Lab.

Update summary

- We have demonstrated that we can extrude and draw a multi-sub-element TP Bi-2212/Ag billet and preserve LAR.
- We have assembled a 3-layer billet with TP bars in core and will soon conduct drawing and extrusion experiments.
- Plans thereafter are to do process development of OP heat treatment of multi-filament wire with ~50 μm cores, measure Ic(B) for the wire, and evaluate wire made with powder from Nexans, MetaMateria, and nGiMat.

Down the road….
Can TP Bi-2212/Ag wire survive cabling?

- The reduced LAR of Ag may make Rutherford cable susceptible to damage from cornering stress.
- Once wire is developed, we will provide samples to LBNL to cable.
- We have successfully fabricated SuperCIC using Bi-2212:

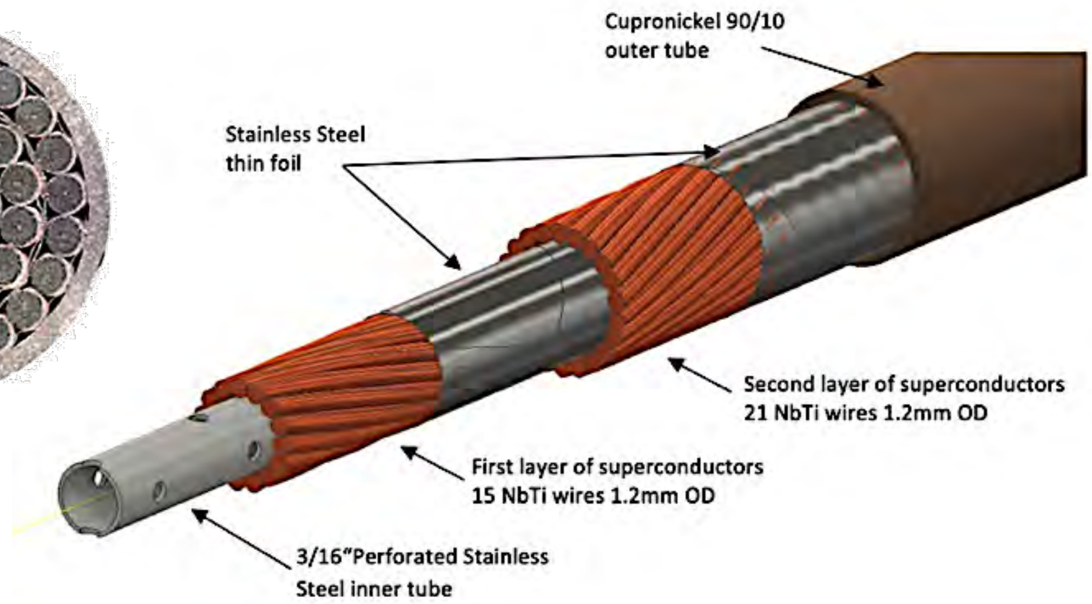


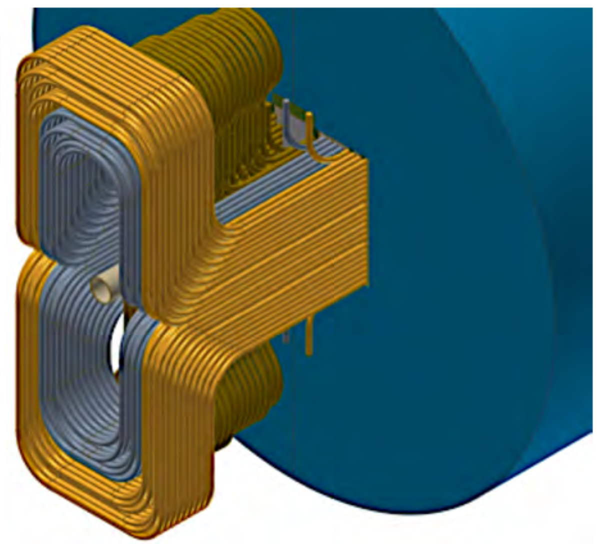
2-layer SuperCIC made using Bi—2212 wires: a) cross-section showing the layers of over-wrap foils; b) blow-up detail showing strands in both layers.

- SuperCIC provides stress management within the cable, may provide better support with less Ag.

2. Nb_3Sn cable-in-conduit

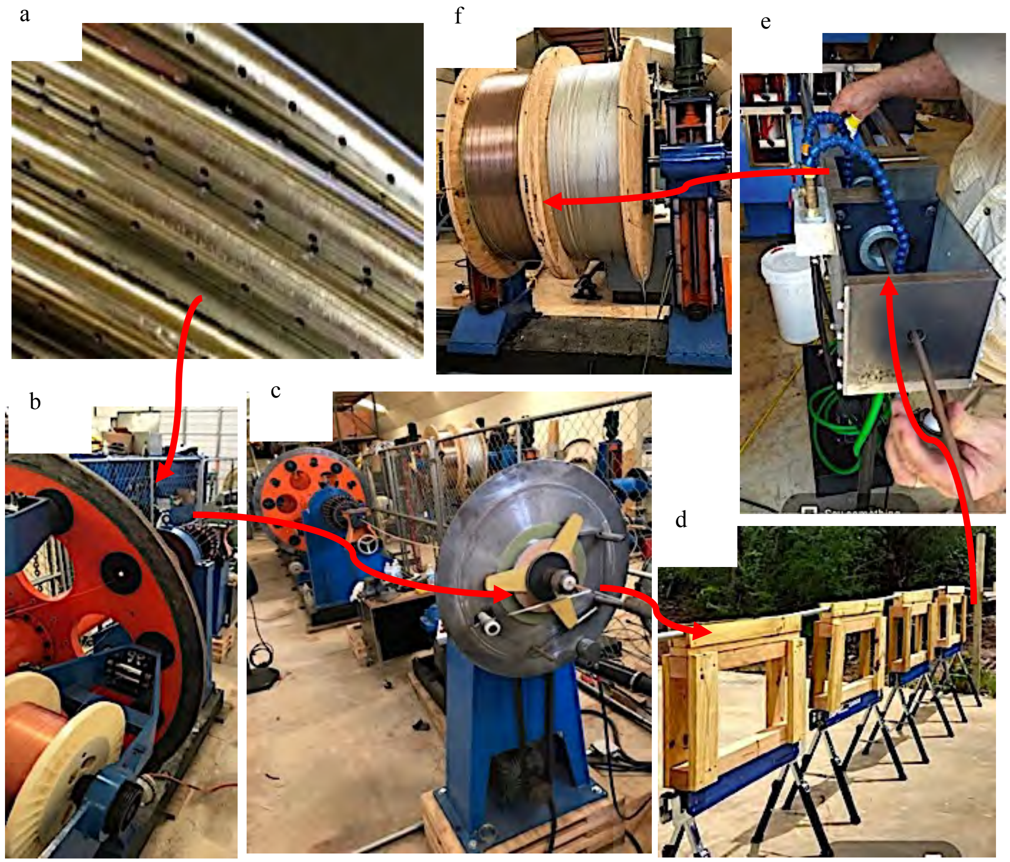
- ATC and TAMU have developed a NbTi cable-in-conduit for use in superconducting magnets.



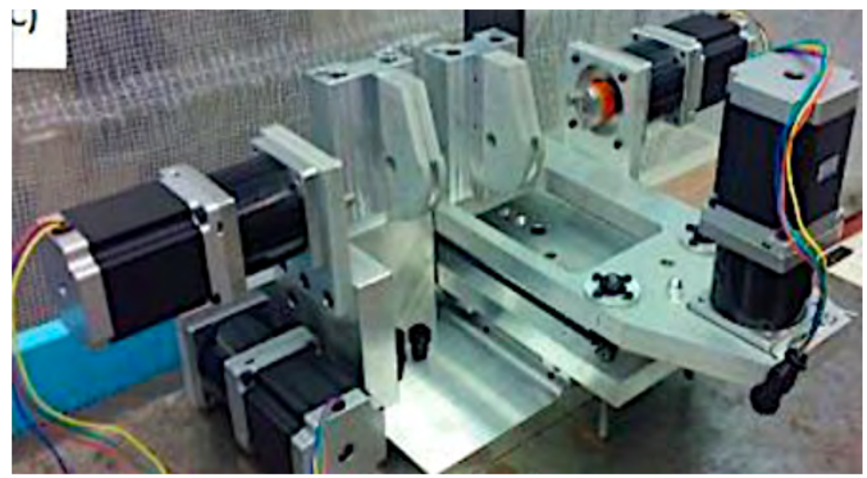


- It provides stress management at the cable level, internal flow of cryogen within the cable, and ability to form small-radius flared ends with support to all wires.

ATC has developed a manufacturing process to make SuperCIC in 150 m lengths



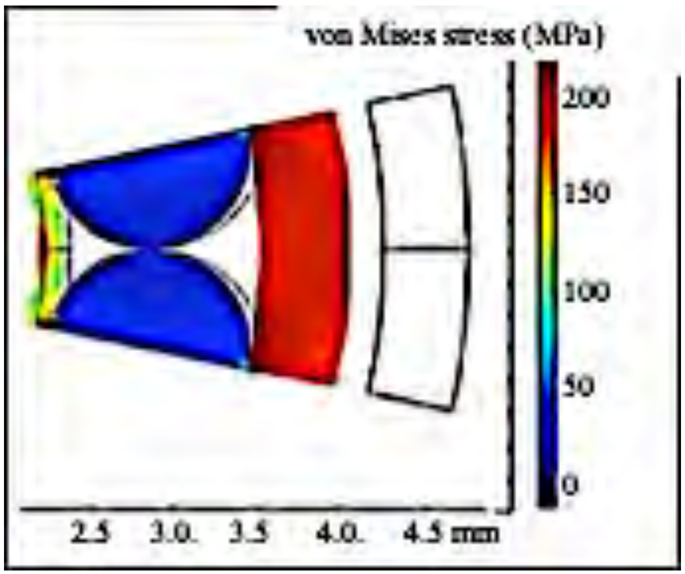
Fabrication of SuperCIC: a) perforated center tube; b) cable superconducting wires onto center tube, c) apply foil over-wrap; d) pull straight 150 m cable through sheath tube with loose fit; repeat b-d for the second layer; e) draw sheath tube onto cable.



TAMU has developed robotic bend tooling to make 8 cm-radius bends

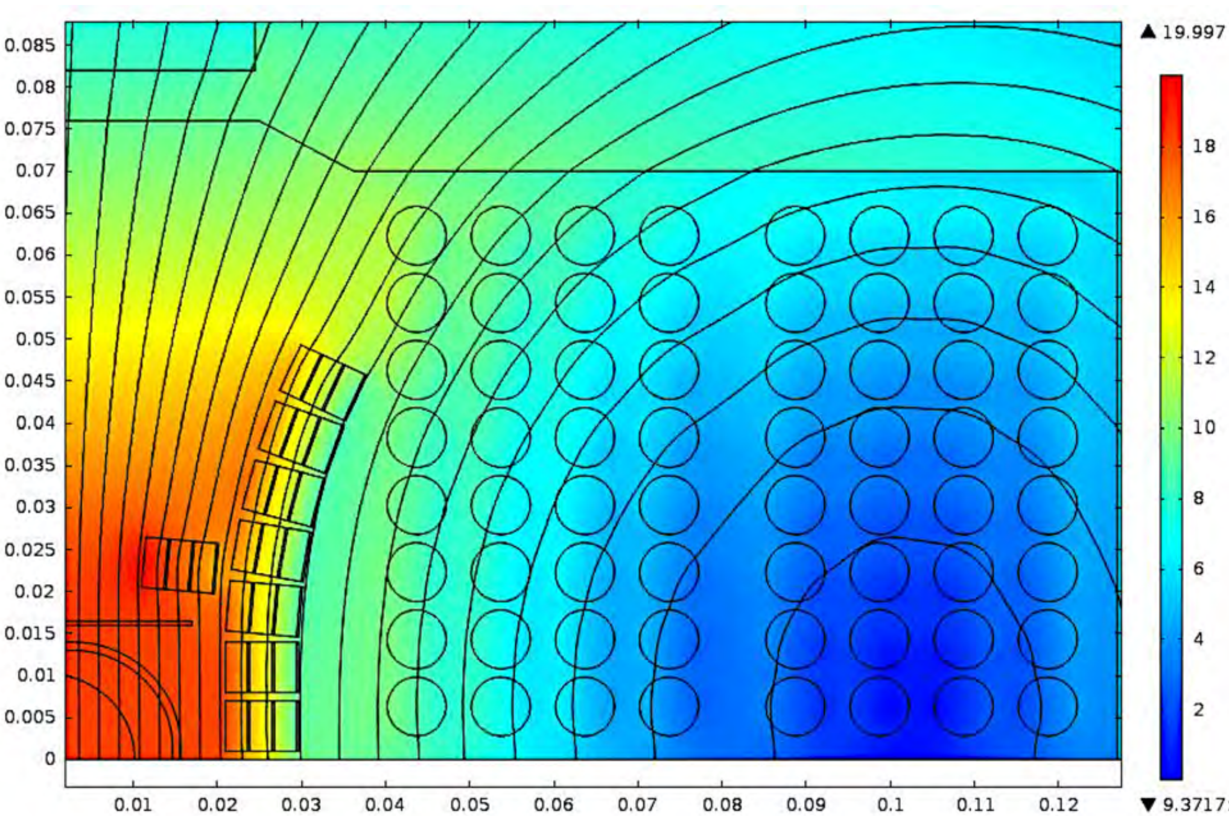
ATC, TAMU, and HyperTech have developed short-length fabrication of SuperCIC using tube-process Nb_3Sn

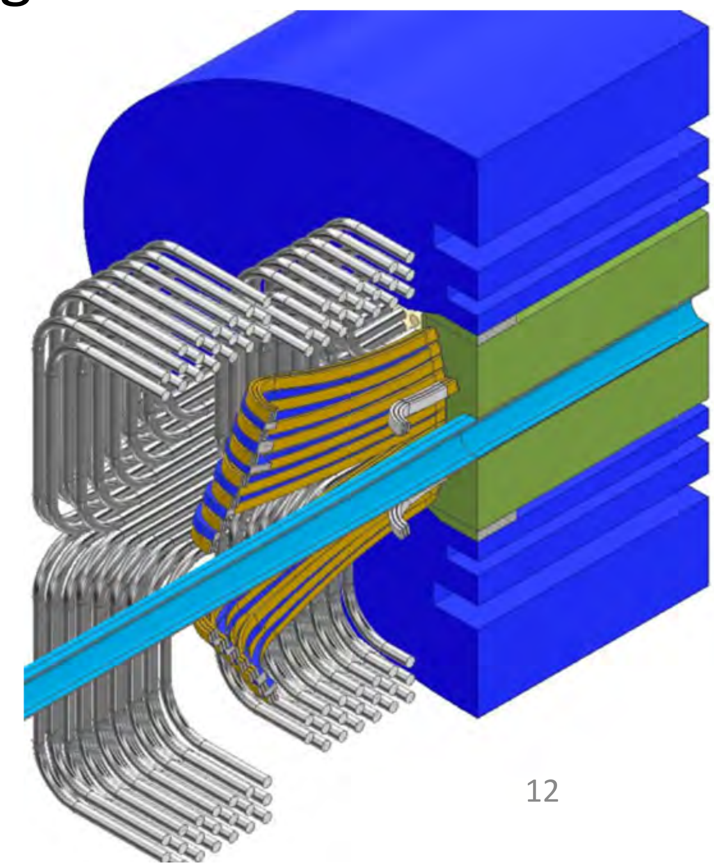
- The perforated center tube is made of 316 SS, the sheath tube is made of aluminum bronze.
- SuperCIC provides stress management at the cable level. The center tube deflects elastically as each wire is compressed against it, so the wires are immobilized (so they cannot move under Lorentz forces), but they are protected from strain by the elastic support from the center tube.



Nb_3Sn SuperCIC for an 18 T hybrid dipole

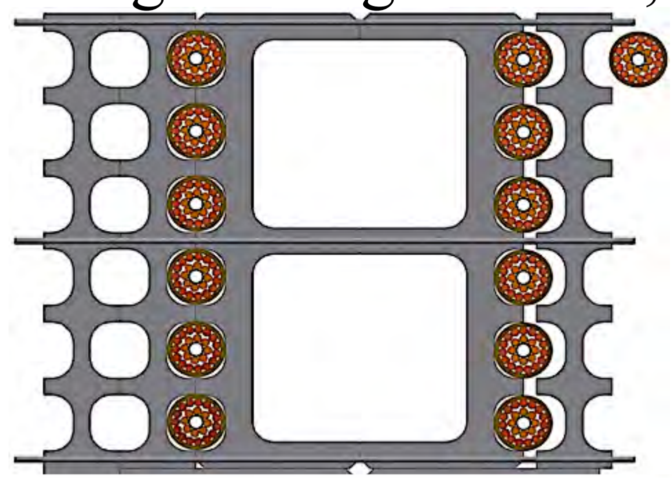
- ATC is funded under **SBIR DE-SC0021688** to develop Nb_3Sn SuperCIC for the outsert winding of an 18 T hybrid dipole:
  - Fabricate short-lengths of single-layer Nb_3Sn SuperCIC, heat-treat, test short-sample limit.
  - Fabricate few-turn winding, test in background field.



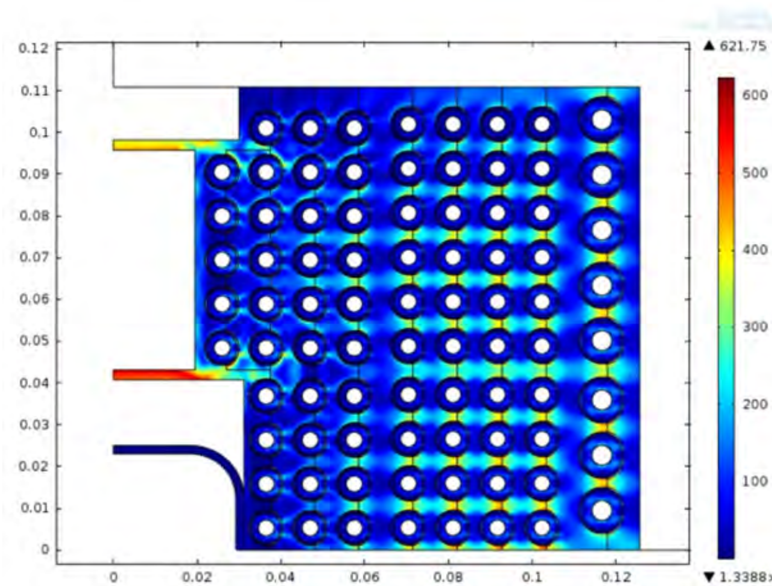


Structural support in SuperCIC outsert

- Plymouth tube fabricates near-net-size extrusions using T16Al4V.
- Support structure is an assembly of interlocking Ti extrusions. The SuperCIC cable is insulated with ceramic coating and S-glass sock, wound into groove in Ti-channel:



- Simulated von Mises stress in the windings and Ti support matrix at 18 T:



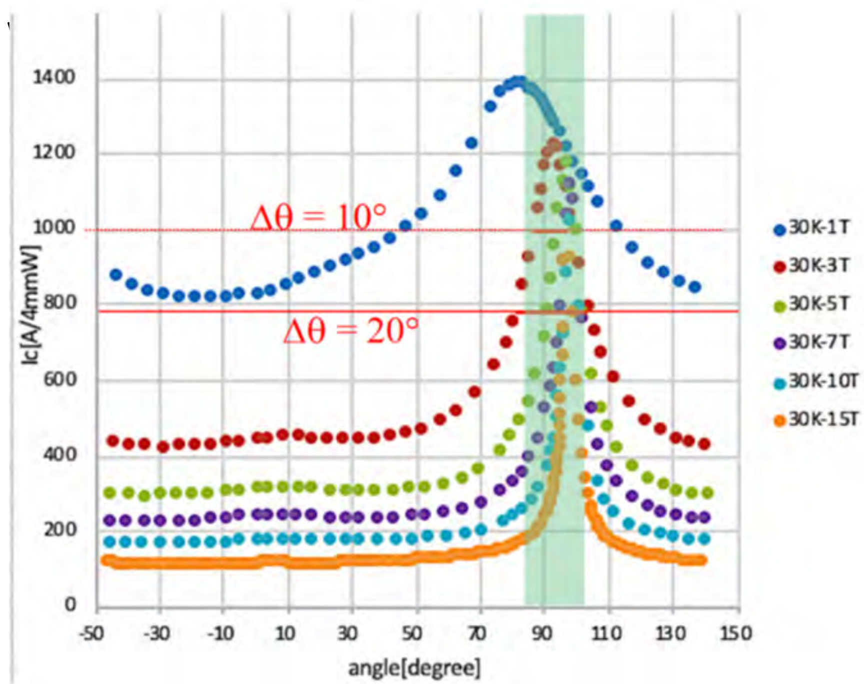
Update summary

- This project has just begun.
- ATC is modifying the SuperCIC cabling line to accommodate low-tension feeds for the Nb_3Sn wire spools, tuning cabling parameters to optimize cable.
- Fabricate short-length SuperCIC segments using HQ-spec RRR wire.
- Heat-treat Nb_3Sn SuperCIC @ATC
- Evaluating options for cold-testing short segments of single-layer cable: 17T @ 12.2 T, 5 K.

3. Conformal REBCO windings for insert windings of high-field dipoles

- REBCO is a wonderful superconductor:
  - It can operate with useful current density up to liquid nitrogen temperature.
  - It can produce very high magnetic field at temperatures of 20-40 K:
  - 1000 A in a 4 mm wide tape at 18 K, 30 K when $\vec{B}$ is ‖ to the tape face.
  - The manufactured tape is ready to use as supplied, and does not require a final heat treatment in a magnet

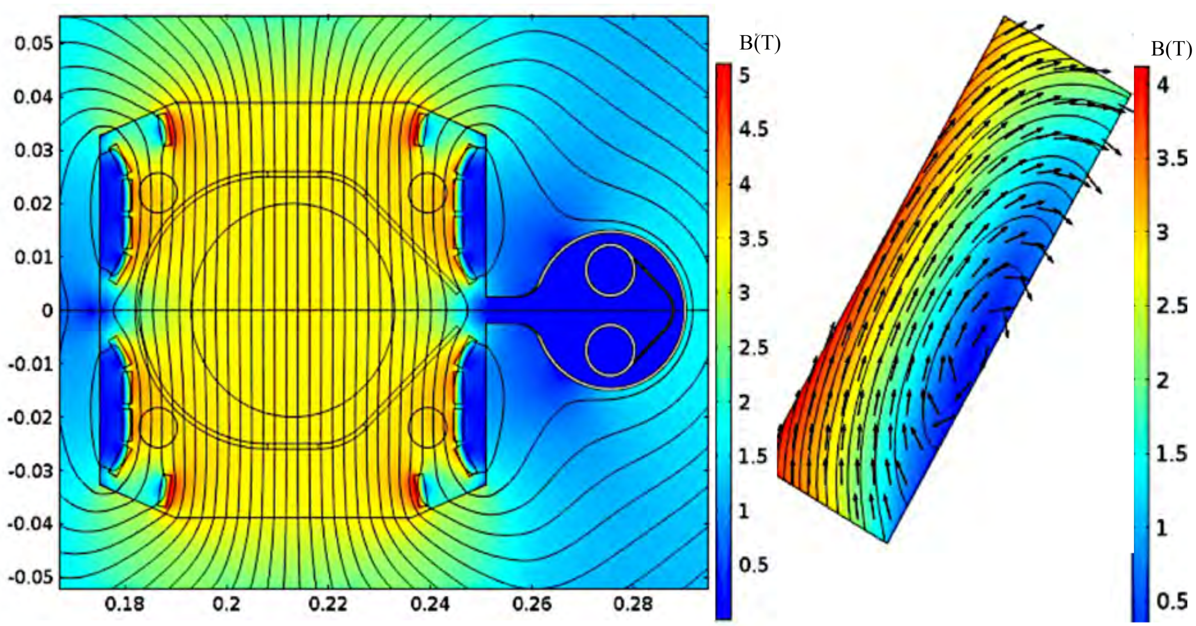
- BUT…
  - REBCO is extremely expensive
  - one 4 mm tape costs ~$60/m.
  - REBCO is an anisotropic superconductor:
  - I_c ~3 times greater for $\vec{B}_{\parallel}$ than for $\vec{B}_{\perp}$.



Can we design a REBCO winding with $\vec{B}_{\parallel}$ everywhere?

In an earlier paper, we showed that we could make $\vec{\boldsymbol{B}}_{\parallel}$ in all turns of the body winding of a 4 T dipole

- Each turn is positioned with its face parallel to $\vec{B}$.
- Each layer of the winding forms a curving current sheet – *conformal winding*.
- Because each layer follows the contours of $\vec{B}$, the conformal condition is preserved for all values of $|B|$.

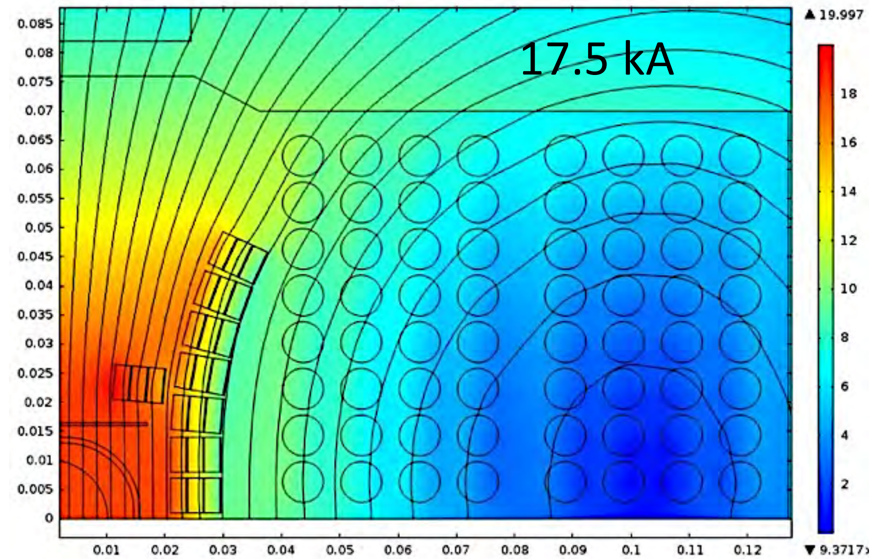


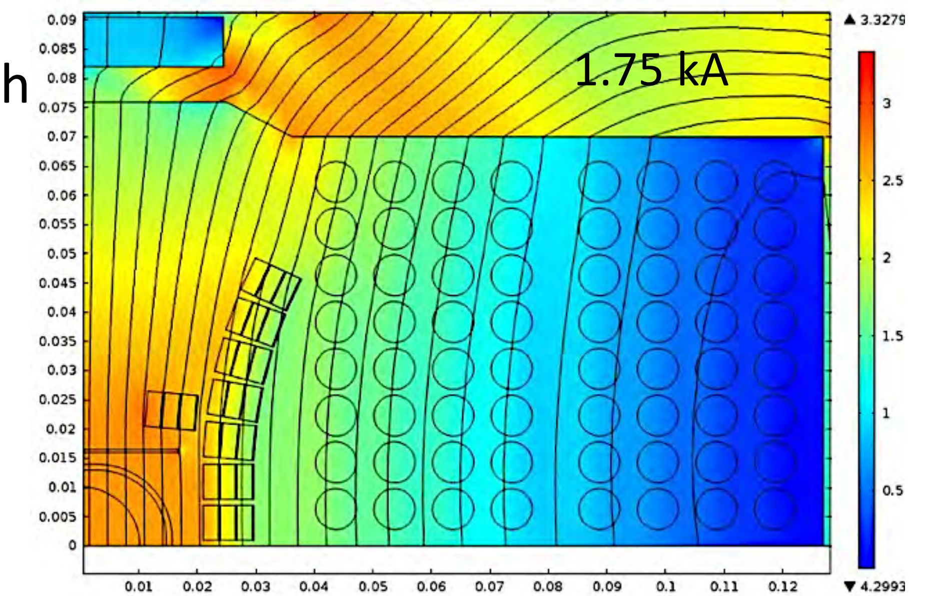
This raises 3 questions:

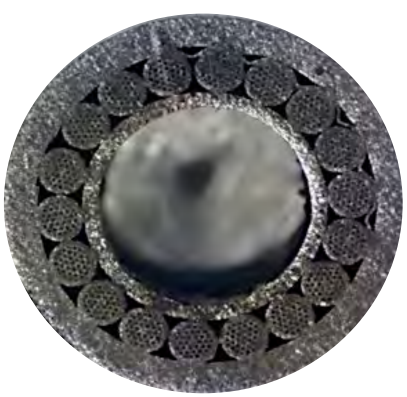
- Could the conformal condition be preserved for a high-field hybrid dipole (steel saturation)?
- Could the conformal condition be preserved in the flared ends of a dipole?
- Could a multi-tape winding be oriented everywhere with $\vec{B}_{\parallel}$ yet be ramped with current sharing?

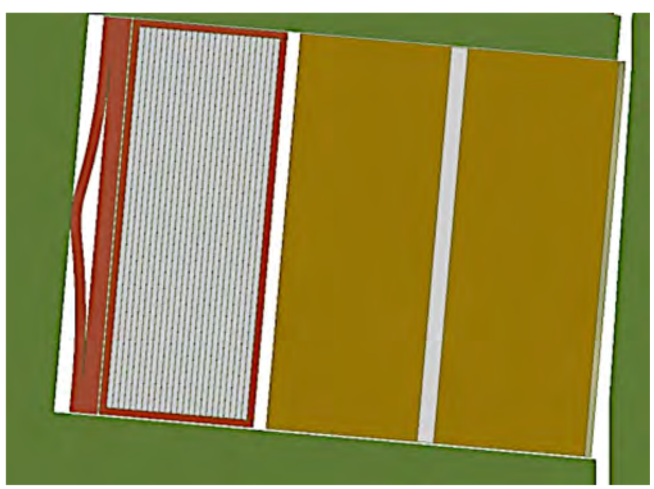
18 T hybrid dipole – body field

- REBCO sub-winding uses flat cable containing 24 6-mm tapes, 4 layers gives ~5 T in the dipole.
- Nb_3Sn sub-winding uses cable-in-conduit (CIC) containing 15 0.8 mm wires, gives ~13 T in the dipole.
- 18.3 T bore field at short-sample. Current limit ~equal in REBCO, Nb_3Sn sub-windings.
- Steel flux plate helps to maintain homogeneity over 10:1 dynamic range.
- Curved boundary of REBCO is optimized for high field, but departs from optimum at lower field.







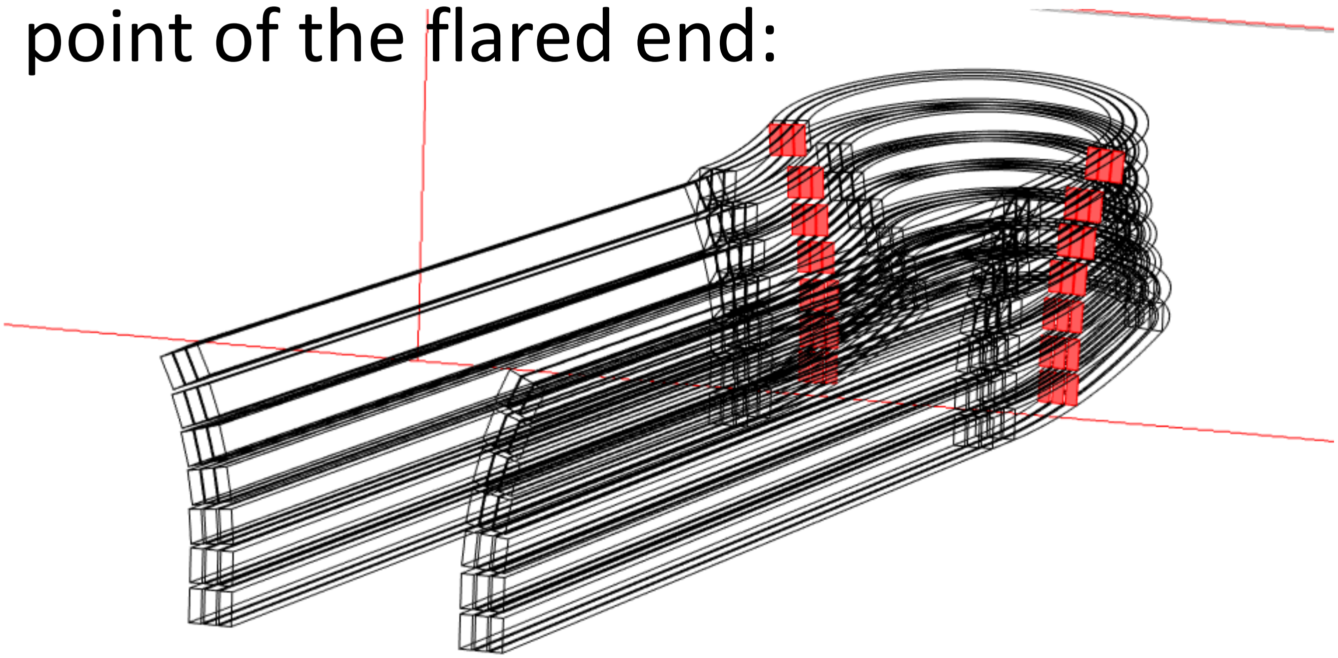


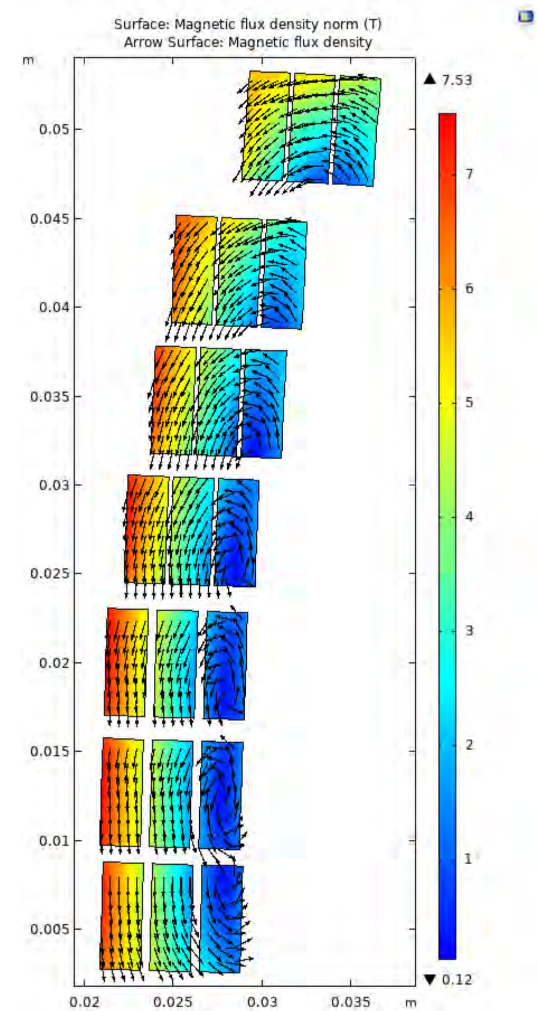
Flared-end REBCO sub-winding

- We are evaluating two geometries for the flared-end windings of REBCO tape-stack cables:

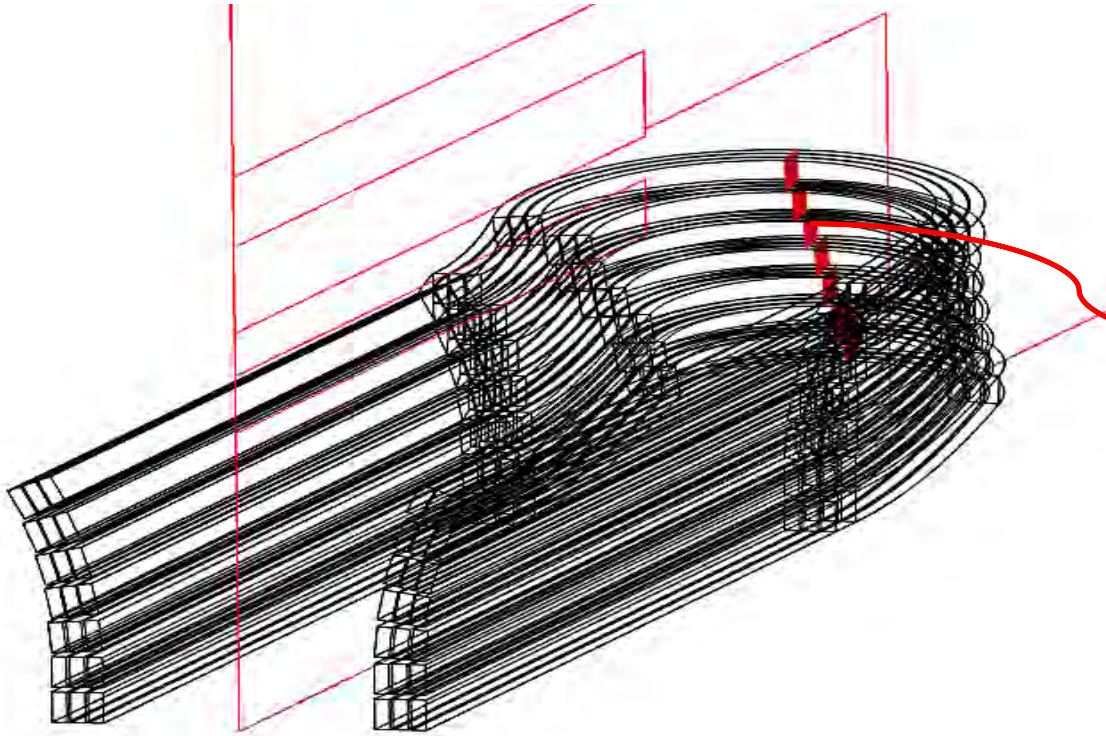
1. Minimum flare angle to clear beam tube:

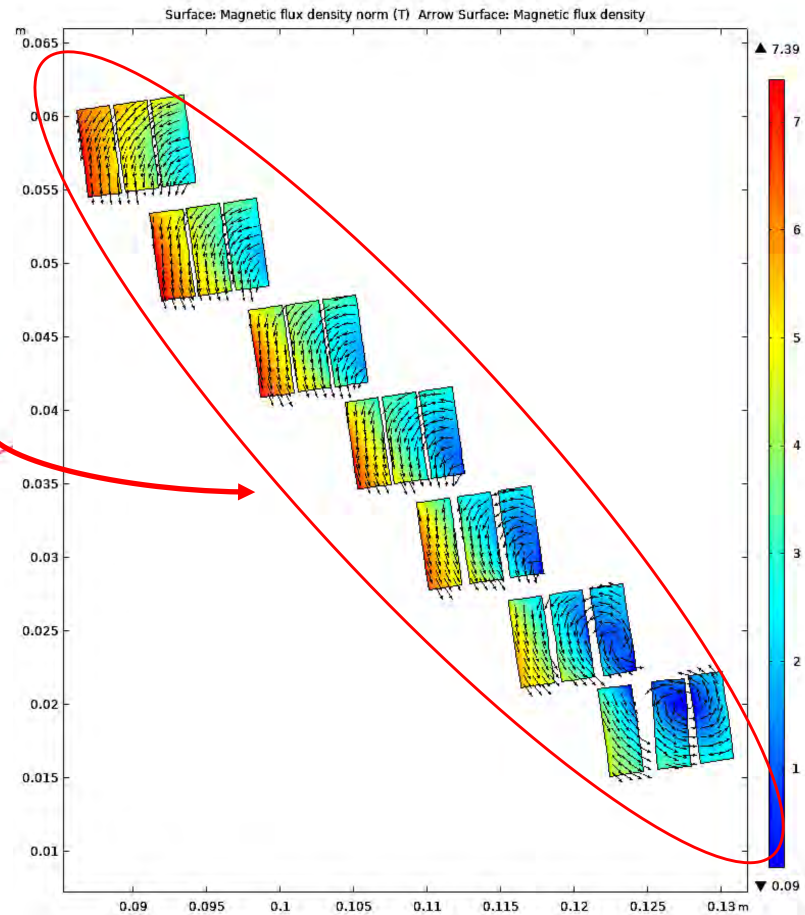
- Field distribution in cross-section slice at 30º point of the flared end:





- Mid-plane of the flared end:



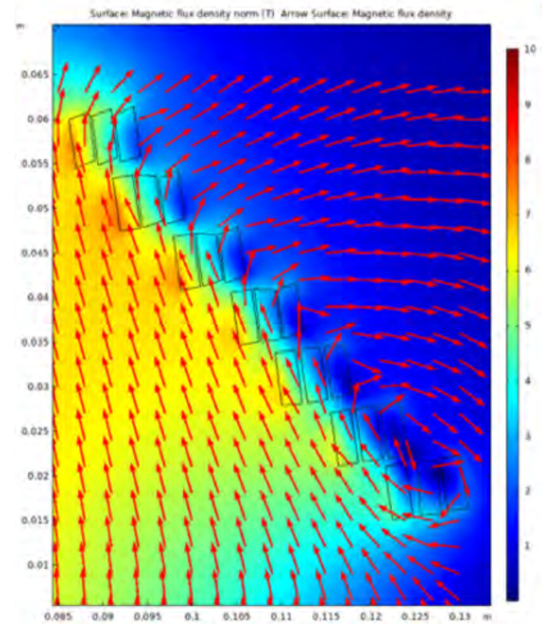


We have developed a macro that calculates I_c for the $|B|$ and θ corresponding to each of the 50 tapes in each of the tape-stack cables each portion of the flared end windings for both the narrow and wide flare geometries.

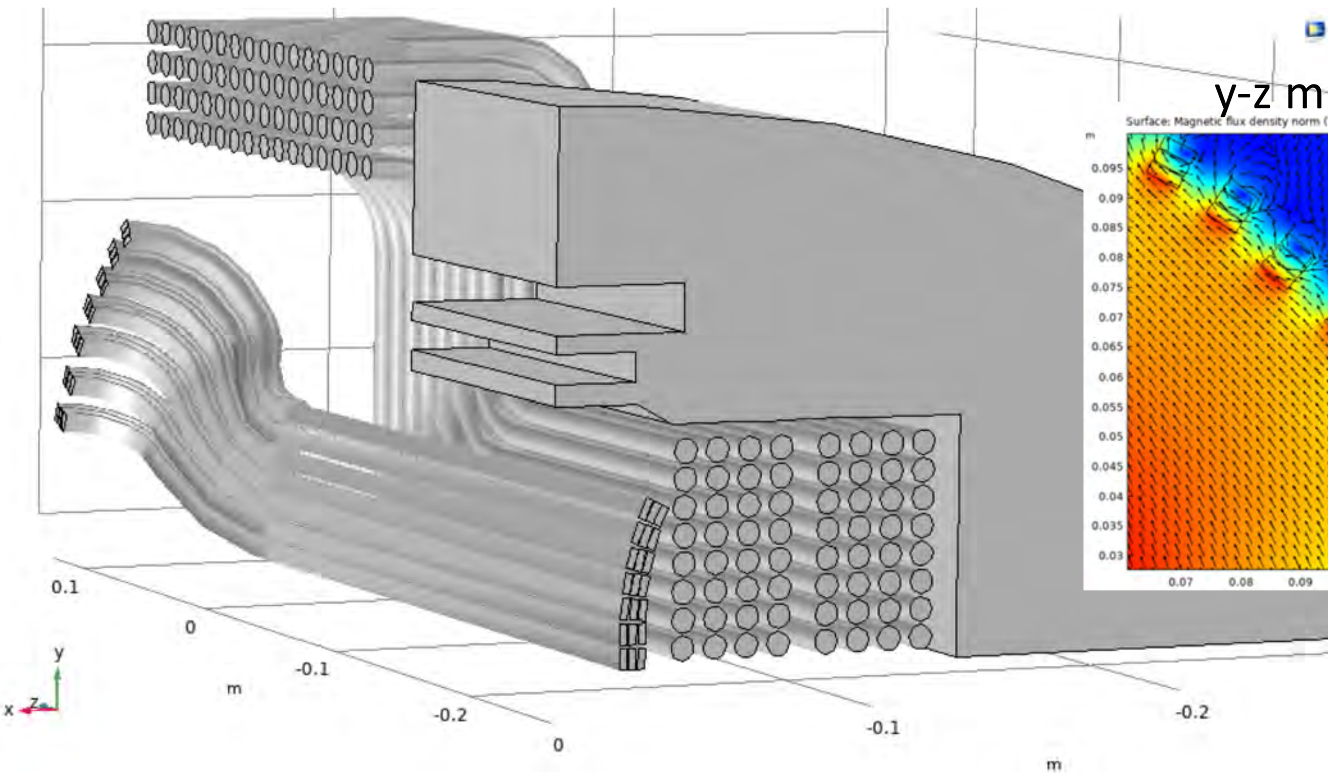
Preliminary conclusion: I_c does not limit B_{max} for either geometry of the flared ends.

Wide-flare ends

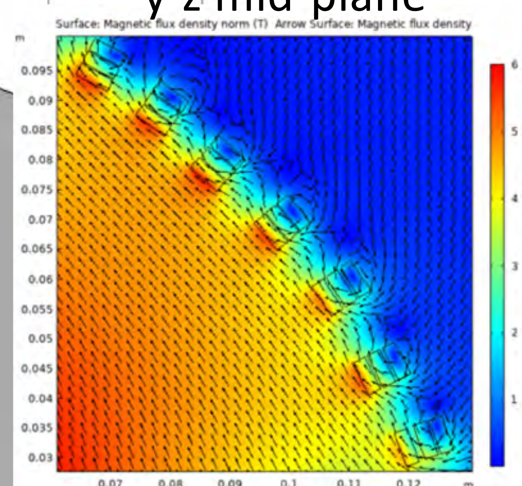
- Flare the Nb_3Sn cables with constant-radius 90º flares.
- Extend the REBCO ends beyond, conformal flare to reduce field @ cable.
- Endeavor to contour flare to maintain $\vec{B}_{\parallel}$.

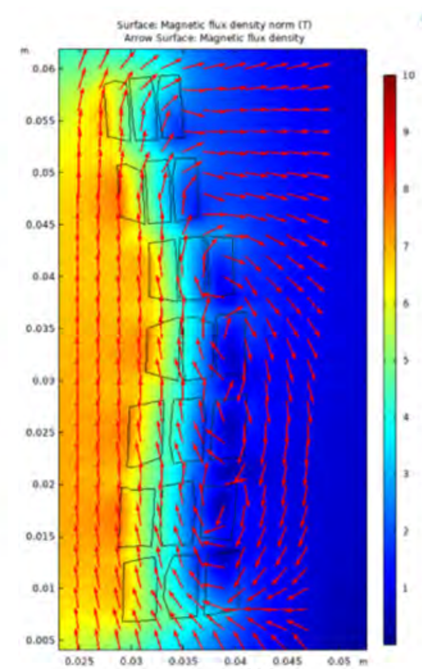


x-z 45º cut



y-z mid-plane

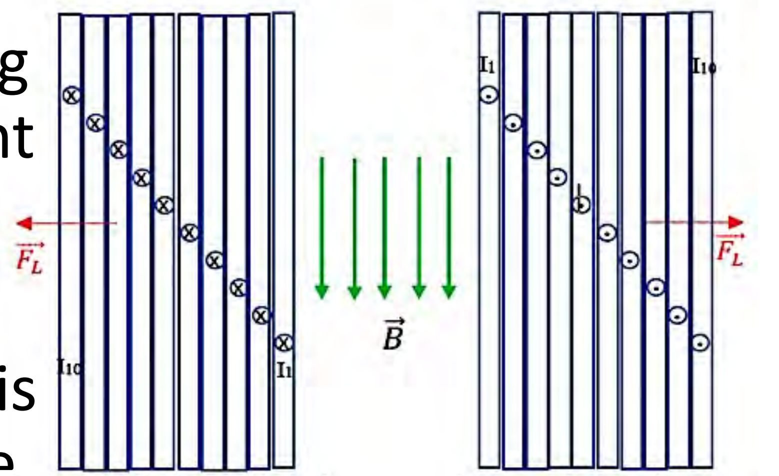




x-y cut @ middle of CIC flare

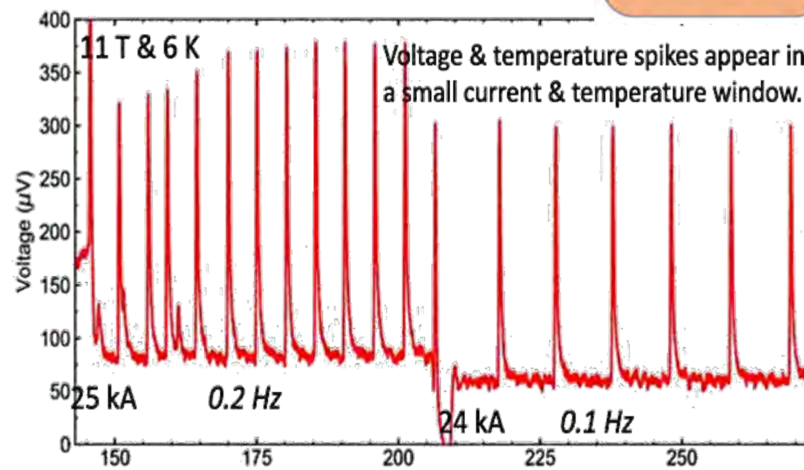
Current-sharing in a REBCO cable

- When current is ramped in a cable containing wires in contact, Lorentz force pushes current towards the outside of the winding at all locations.
- Unless the cable is twisted or transposed, this force tends to concentrate current and cause per-mature quench.



- As current in the outermost tape approaches critical current, that tape develops a non-zero electric field, which pushes additional current to the next-inner tape.
- This process repeats as each tape reaches its capacity, and produces a set of voltage spikes.
- But for REBCO, the I/V transition is gentle and can provide a domain of dynamic stability.

- Ten Kate *et al*. observed this in a large test winding, even with a CIC of twisted CORC cables, because of isolation of bundles in the leads:
- As current in the outermost tape approaches critical current, that tape develops a non-zero electric field, which pushes additional current to the next-inner tape.
- This process repeats as each tape reaches its capacity, and produces a set of voltage spikes.
- But for REBCO, the I/V transition is gentle and can provide a domain of dynamic stability.

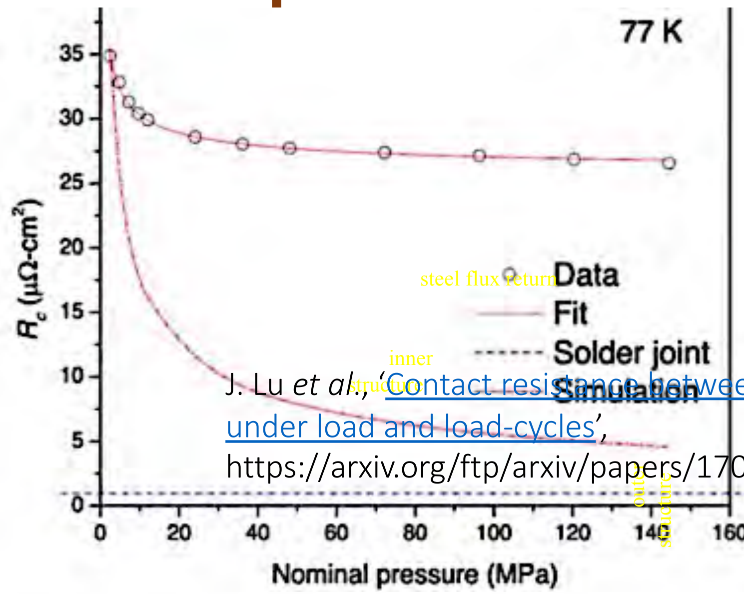


Voltage spikes associated with successive stages of current-sharing in the testing of a REBCO CIC conductor:

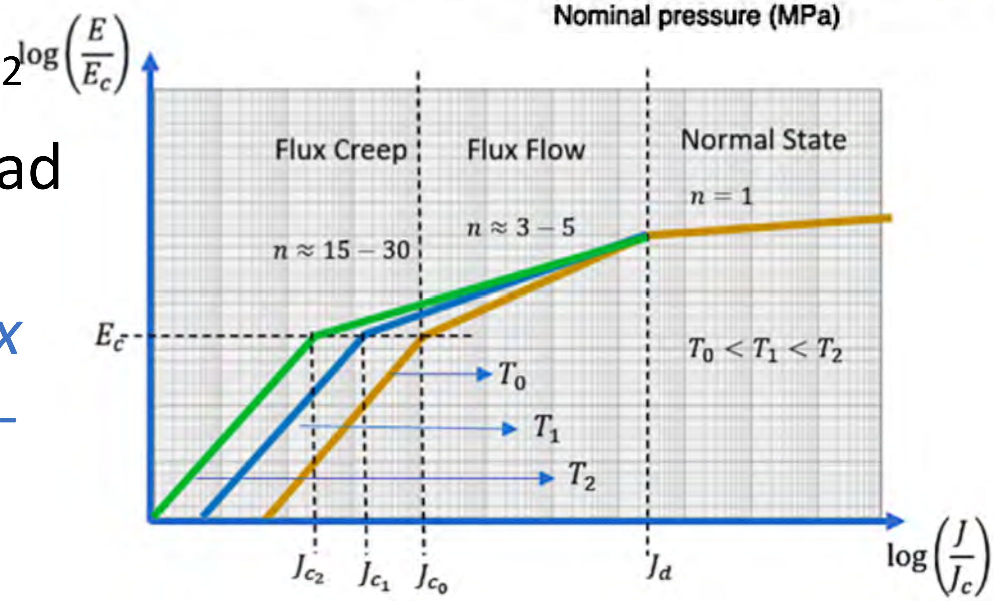
T. Mulder *et al*., Development of ReBCO-CORC conductors and their magnet technology at CERN', ICMC 2019

Flux creep, enhanced current-sharing: dynamic stability as current is ramped

- Current-sharing relies critically upon the face-face contact resistance between tapes
- We developed a laminar spring that provides S_0~1 MPa of uniform compression in a flat-profile package, and sustains it through a stack of 24 tapes.
- Lu *et al*. found that 1 MPa compression produces 35 $\mu\Omega$-cm^2 contact resistance between Cu-clad faces of REBCO tapes.
- REBCO exhibits *flux creep* and *flux flow*. With sufficiently good tape-tape transport the dynamics for current transfer should provide stability as current is ramped.

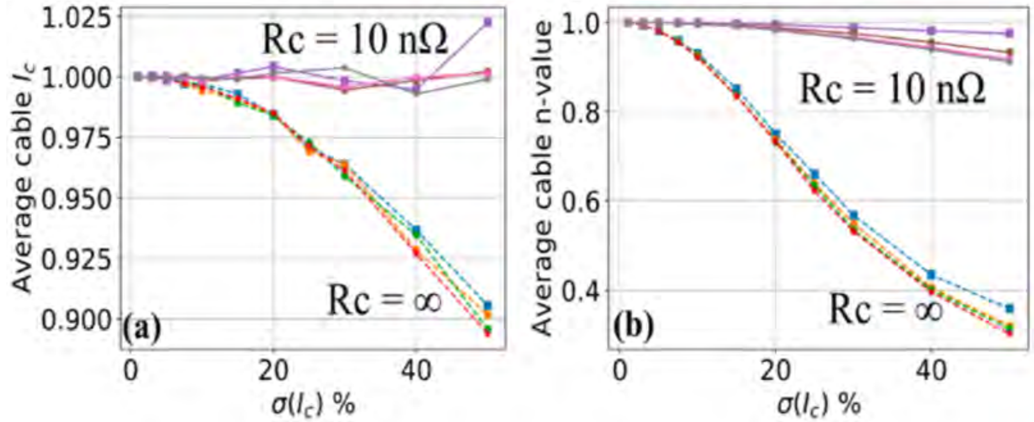


J. Lu *et al.*, 'Contact resistance betwee[n] ... under load and load-cycles', https://arxiv.org/ftp/arxiv/papers/170...



F. Trilaugh *et al*., 'Essential material knowledge and recent model developments for REBCO-coated conductors in electric power systems', Materials **14**, 1892 (2021)

We are developing a multi-physics model of current sharing and dynamics during ramp



Average cable parameters as a function of Ic variation for different numbers of tapes: a) cable I_c; b) n value.

A.C.A. Martinez *et al*., 'Electric-circuit model on the inter-tape contact resistance and current sharing for REBCO cable and magnet applications', IEEE Trans. Appl. Superconduct. **30**, 4, 2972215 (2020).

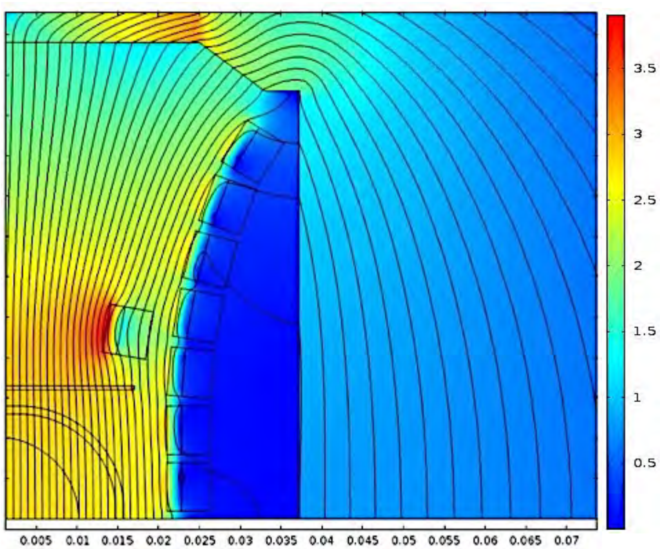
- Martinez *et al*. modeled current transfer in a stacked-tape cable and found that a region of cable with coupling resistance ~10 nΩ is effective in equalizing current among its tapes. The laminar spring sustains 1 MPa compression, so the characteristic length of cable for stability is $L \sim \frac{35\mu\Omega - cm^2}{10n\Omega \cdot 6mm} = 60\mathrm{m}$.
- That is about one turn for a collider dipole, so it may suffice to stabilize ramping without driving a quench.

Future plans: magnetic modeling

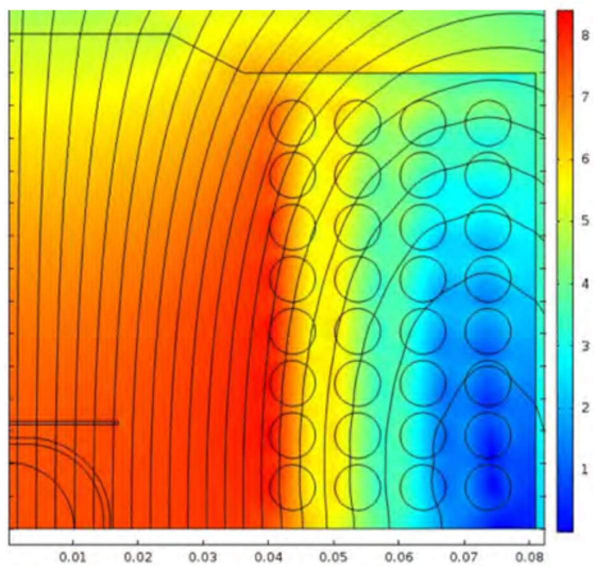
- We are undertaking a systematic study of the 3-D magnetics of the 18 T dipole to determine what is the most effective geometry to preserve conformal geometry in the body and ends.
- We are developing a multi-physics model of current dynamics in the REBCO winding as the dipole current is increased. The model will be used to predict the dynamics of current transfer and voltage spikes that should be produced. Effects of heat transfer, stress management, and quench criteria will be studies.

Future plans: build/test a progression of sub-scale model dipoles

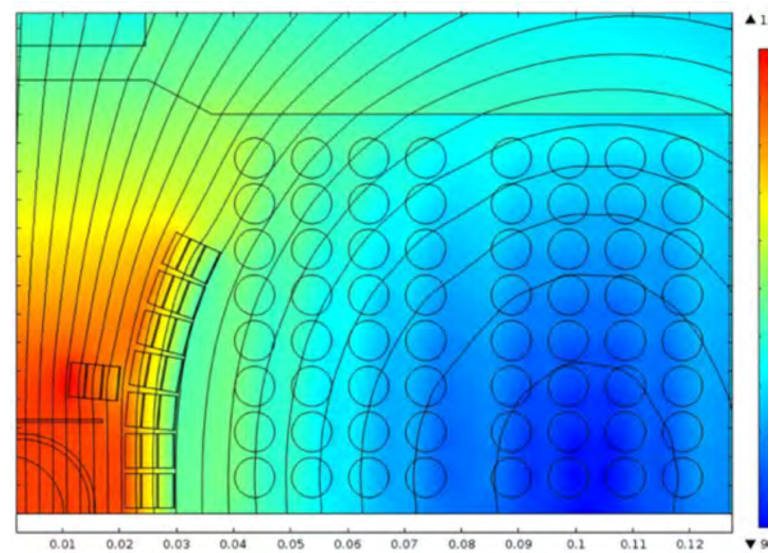
	TAMU4	TAMU5	TAMU6	TAMU7	
Bore field @ 4.2K short-sample	2.7	8.3	10.9	18.3	T
Cable current (windings in series)	15.5	20	15.5	15.5	kA
REBCO: #tapes/cable x #cables/shell x #shells	5x16x1		25x 16 x 3	25x 16 x 3	
Nb_3Sn CIC: #wires/CIC x #cables/layer x #layers		17x 16 x 4	17x 16 x 4	17x 16 x 8	
B_{max} in REBCO, CIC	2.8	9.2	12.0	18.5, 11.8	T
Sextupole @ full field, injection field		44	46	27, 35	un
Total conductor cost in 1m dipole	16	31	249	310	K$



TAMU4: Single-shell REBCO sub-winding, to be built by ARL.



TAMU5: 4-layer Nb_3Sn SuperCIC sub-winding, to be built by ATC



TAMU7: 8-layer Nb_3Sn outsert, to be buil by TAMU and ATC.

Update summary

- REBCO inserts offer great benefit for dipoles of 16-24 T.
- REBCO is ruinously expensive, and the conventional design methodology of twisted cables to homogenize current distribution during ramping limits the current capacity to ~1/3 of what a REBCO tape can support when aligned with the field at conductor.
- We are developing a conformal winding strategy that could preserve that full current capacity, and a structured cable design that could provide optimum Intertape resistance for current-sharing.
- The strategy is related to the NI strategy that provides excellent stability in stack-of-pucks solenoids.
- This is a work in progress – we are developing the 3-D magnetics to preserve the conformal geometry in the flared ends, and we are developing the multi-physics modeling of current sharing during ramping.