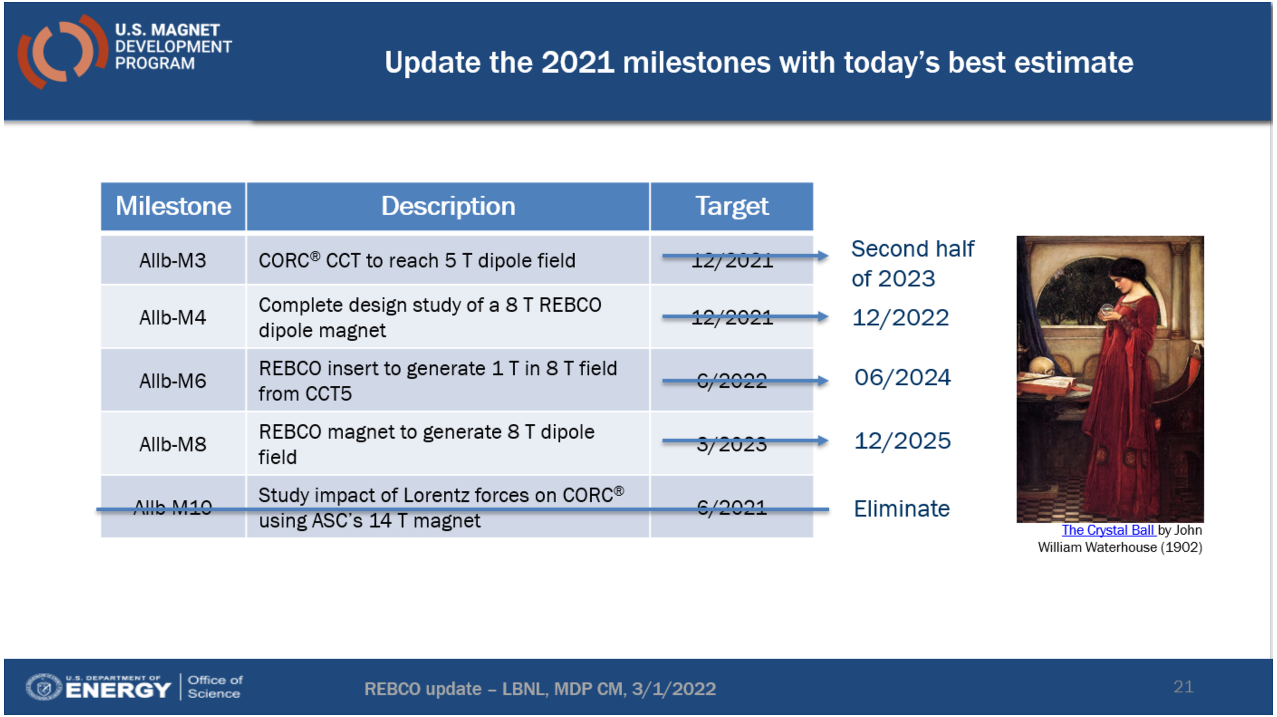
U.S. MAGNET
DEVELOPMENT
PROGRAM

REBCO technology – LBNL report and conductor needs

X. Wang

MDP Collaboration Meeting, 22 March 2023

A year ago



Update the 2021 milestones with today's best estimate

Milestone	Description	Target	
AIIb-M3	CORC® CCT to reach 5 T dipole field	~~12/2021~~	Second half of 2023
AIIb-M4	Complete design study of a 8 T REBCO dipole magnet	~~12/2021~~	12/2022
AIIb-M6	REBCO insert to generate 1 T in 8 T field from CCT5	~~6/2022~~	06/2024
AIIb-M8	REBCO magnet to generate 8 T dipole field	~~3/2023~~	12/2025
~~AIIb-M10~~	~~Study impact of Lorentz forces on CORC® using ASC's 14 T magnet~~	~~6/2021~~	Eliminate

The Crystal Ball by John William Waterhouse (1902)

REBCO update – LBNL, MDP CM, 3/1/2022

21

- C3, AIIb-M3
  - Generate 5 T and measure the field quality
  - A 6-layer CCT dipole magnet using CORC® wires
  - We are practicing with C3a, the 3-turn version of C3

- STAR® magnet status
  - To keep conductor options open
  - AIIb-M6

- Next magnet toward 8 T dipole field, AIIb-M4 / M8
  - Also needed for a hybrid to reach 20 T
  - Magnet options
  - Conductor needs

C3 wire to be delivered in 2023

- ACT plans to deliver the C3 order by October 2023
  - Received 10 km long HM tapes, ~ 8 km for C3
  - Start making wires in April 2023

- We survived the growing pains
  - ACT started ordering the C3 tapes in March 2019
    - Specified I_c for the first time: > 350 A at 4.2 K, 6 T
  - SuperPower started delivering in December 2020, 21 months later
  - More on Friday's experience talk

What do we need to make C3 by December 2024?

- Complete the practice with C3a
  - Gain experience in winding, termination, wire performance, diagnostics
  - Assemble in July, test in September 2023

- Make C3 mandrels
  - 6 layers, $85 k, 6-month lead time
  - Start machining after July 2023, in case of changes from C3a experience
  - Secure the funding to minimize delay

- Access to key staff
  - Contract ends in May 2023; working with the lab to keep the door open
  - Significantly reduce the risks of C3 delivery

…, and some good luck

We expect to test C3a in September 2023

Five down, three to go

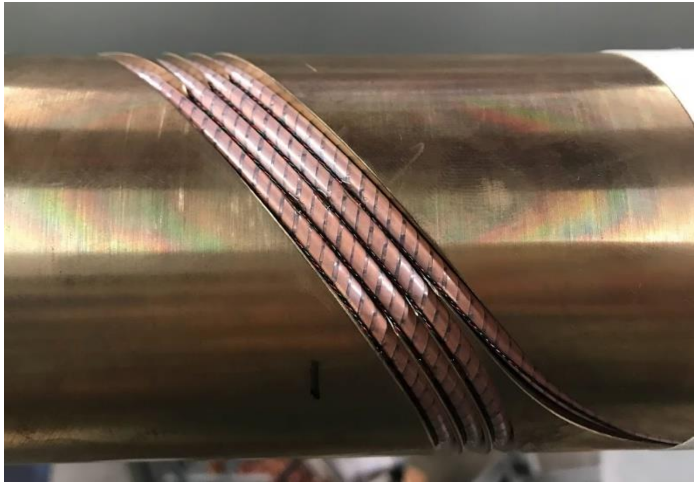
Layer	Conductor type	Complete date
1	AP	8/2022
2	AP	9/2022
3	AP	11/2022
4	AP	1/2023
2b	HM	2/2023
5	HM	4/2023
6	AP	5/2023
1b	HM	6/2023

- Assembly procedure works?
- Performance of each layer after assembly?
- Performance of the HM conductor at 4.2 K?

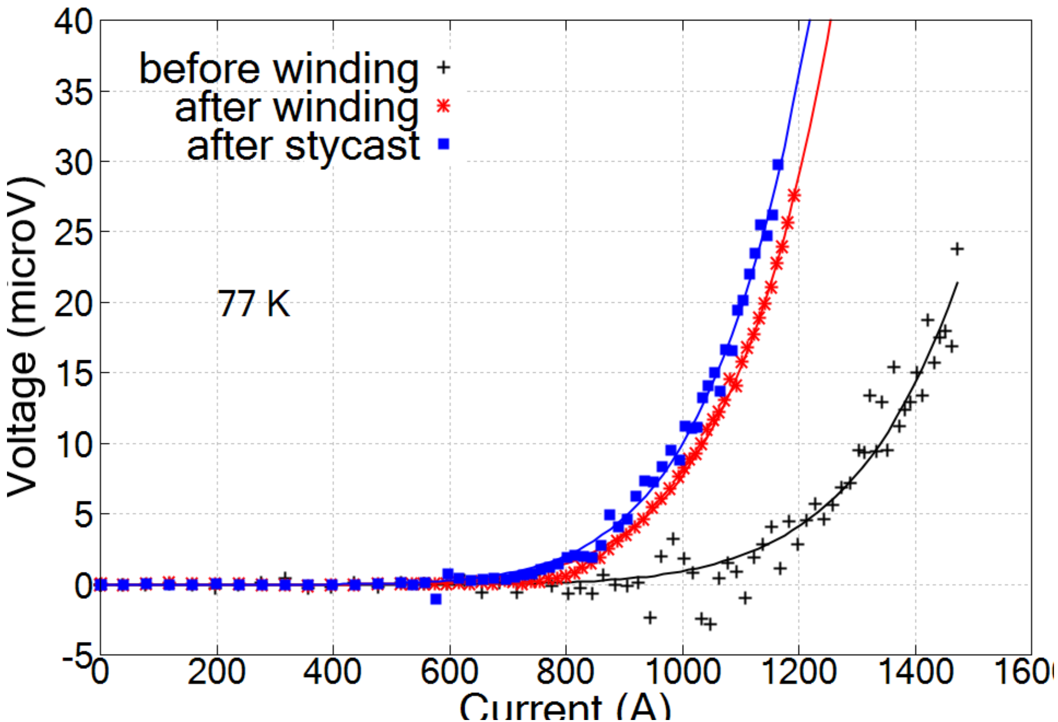
The 3-turn practice provides excellent opportunities to learn

Probe conductor performance
Develop coil fabrication procedure

Co-wound v-tap and fiber;
Maxim's new sensor in Layer 2 [see his talk on Thursday]

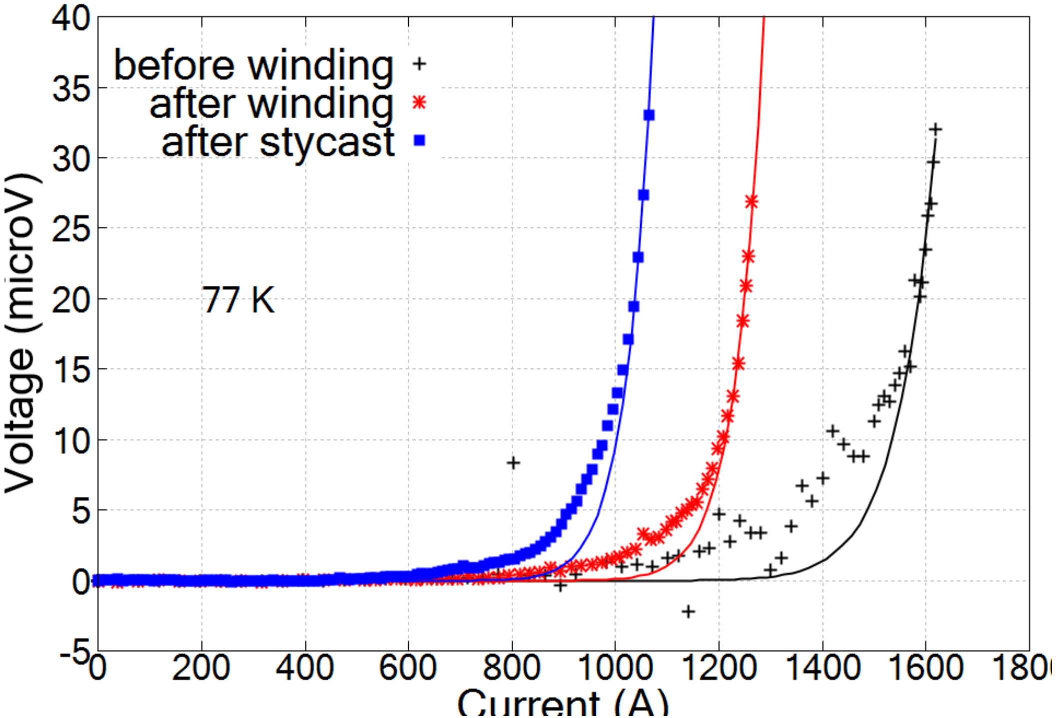


Layer 1, AP wire, I_c evolution at 20 µV criterion: 78% retention after winding, 75% retention after stycast



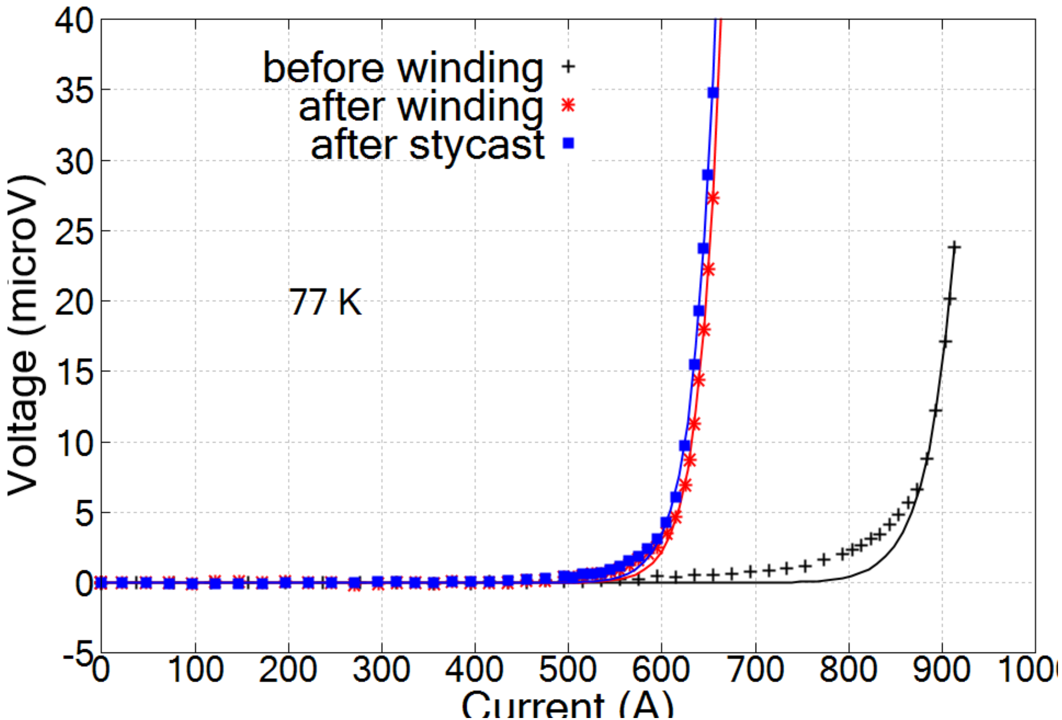
- *n* value for all three cases: 7 – 8

Layer 2, AP wire, I_c evolution at 20 μV criterion: 79% retention after winding, 65% retention after stycast



- Unclear on large I_c degradation after painting Stycast
- Early voltage rise
- *n* value: 18 – 24

Layer 2b, HM wire, I_c evolution at 20 µV criterion: 73% retention after winding, 72% retention after stycast



- Early voltage rise
- *n* value: 27 – 30

Evolution of the transport performance for the first five layers

Measured I_c and *n* value

Layer	Conductor	R_{min} (mm)	Before winding	After winding	After Stycast
1	AP	30	1460 / 8.0	1145 / 7.7	1103 / 7.2
2	AP	35	1588 / 19.1	1250 / 24.0	1035 / 17.8
3	AP	30	1550 / 20.4	1268 / 24.9	1245 / 22.9
4	AP	35	1379 / 10.7	1124 / 13.2	1057 / 12.0
2b	HM	35	908 / 30.7	660 / 28.4	652 / 27.0

- Compared to AP wires, HM wires show 40% lower I_c at 77 K and consistently high *n* value > 25

Evolution of the transport performance for the first five layers – normalized

I_c normalized to that before winding

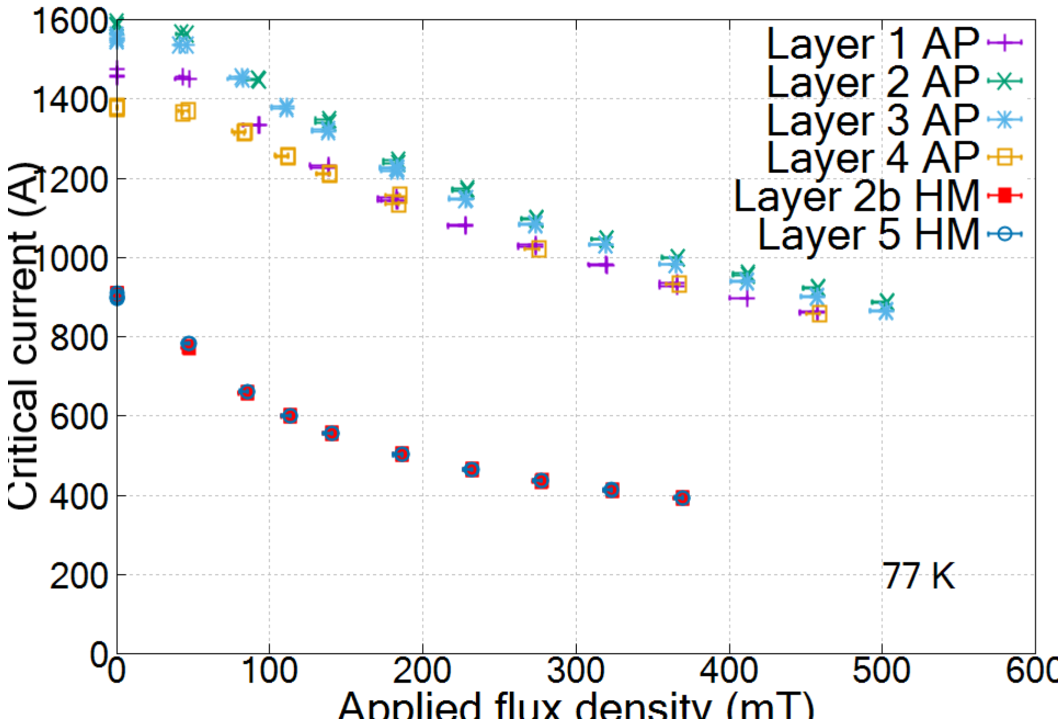
Layer	Conductor	R_{min} (mm)	Before winding	After winding	After Stycast
1	AP	30	100%	78%	76%
2	AP	35	100%	79%	65%
3	AP	30	100%	82%	80%
4	AP	35	100%	82%	77%
2b	HM	35	100%	73%	72%

- AP wires 18% - 22% I_c reduction after winding; HM wires show a higher reduction 27%!
- After painting Stycast, typically < 3% reduction; two outliers

Making sense of the data to assess the fabrication procedure

- Start with the field dependence of the wire at 77 K
- Test the wire inside a LN_2 bathtub
    - Bend radius > 100 mm
- Measure the I_c in a background field up to 0.5 T
- The transverse field covers several turns of tapes in the wire

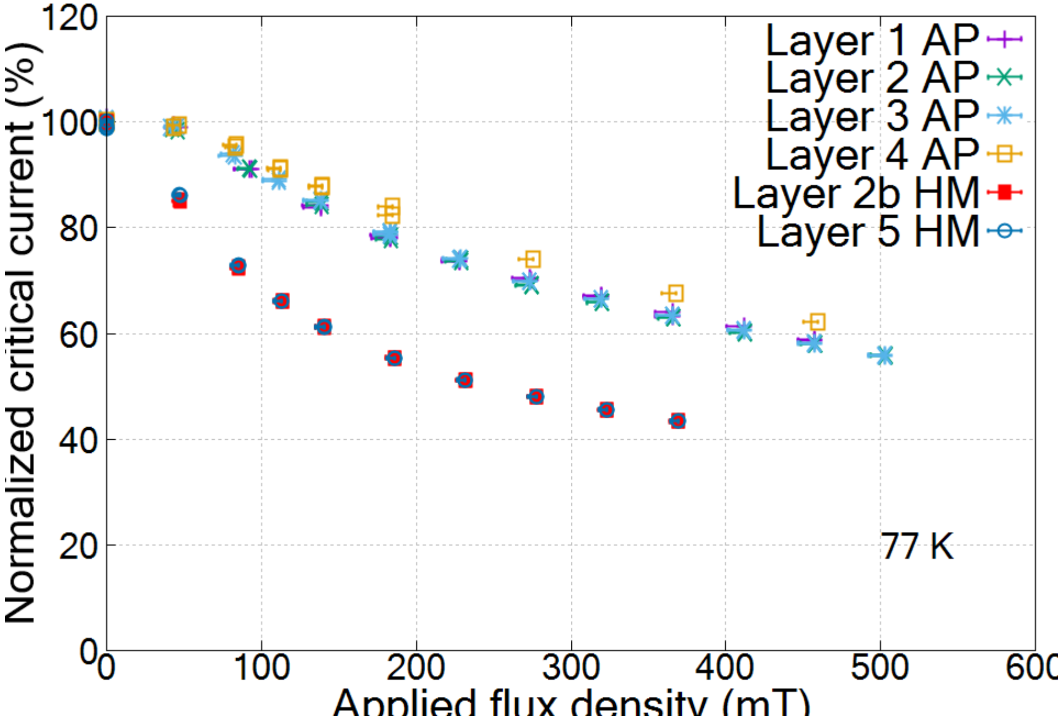
$I_c(B)$ of the conductors in the first six layers



L1: 2.3 m
L5: 3.6 m

- Self-field I_c of AP wire segments varies between 1400 – 1600 A. Variation along the length? Handling? Termination?
- Segments of HM wires similar

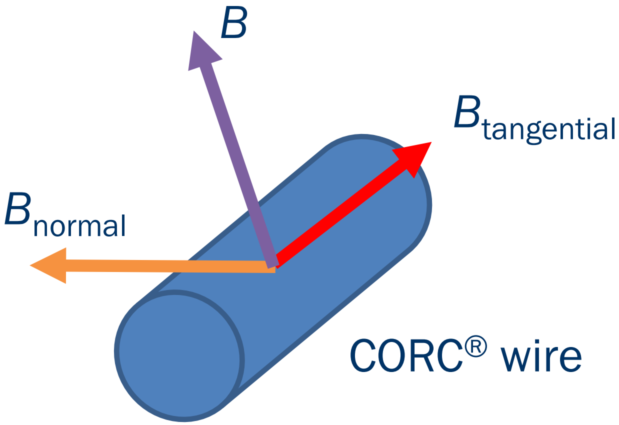
$I_c(B)$ of the conductors in the first six layers – normalized

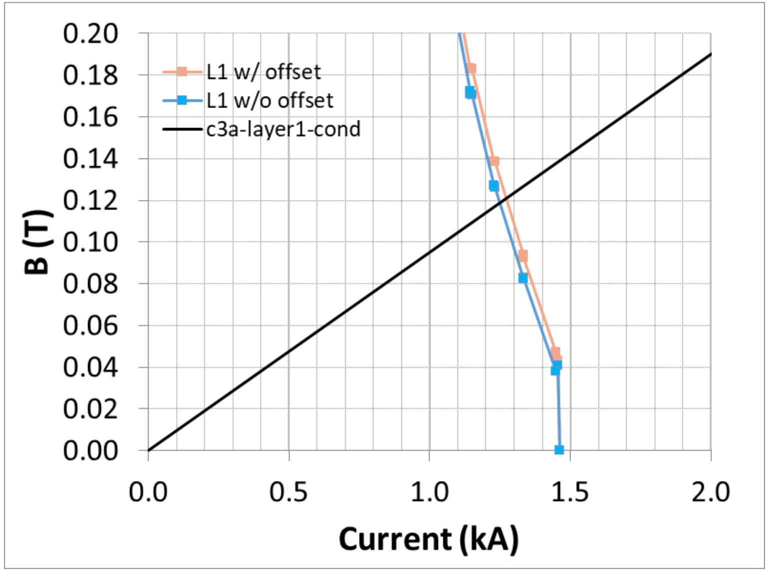


- Similar field dependence among AP segments, despite varying self-field I_c
- Stronger field dependence in HM wires
- AP and HM tapes use different pinning mechanisms

Suppose the wire has an uniform I_c, what's the impact of self-field after winding?

- We use the field component transverse to the wire axis to determine the expected coil I_c





Can explain large reduction in Layer 2b; measured I_c lower than expected from the self-field effect

Percentage wrt to the I_c before winding

Layer	Conductor	R_{min} (mm)	Expected	Measured	Difference
1	AP	30	86%	78%	-8%
2	AP	35	86%	79%	-7%
3	AP	30	87%	82%	-5%
4	AP	35	91%	82%	-9%
2b	HM	35	78%	73%	-5%

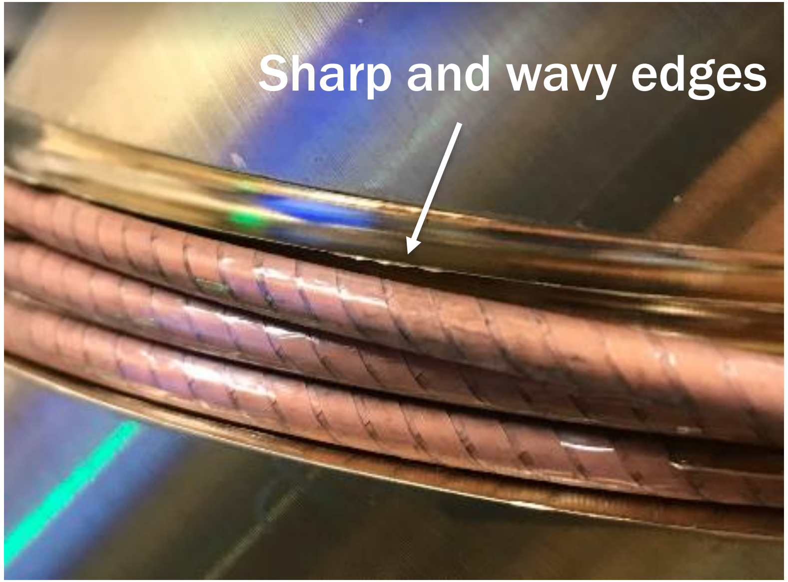
- Stronger field dependence in HM wires explains the behavior of Layer 2b
- Can we attribute the difference to degradation due to bending and handling?

No obvious issue found in the new termination concept at 77 K

- Another enabling contribution from talented staff to address the magnet need
- Working at 77 K with I < 1500 A, consistent behavior from 12 terminations made so far
- Next to measure the high-current performance at 4.2 K
- Shared with FNAL and Kyoto University for further improvement

Winder Mark #2 wound six 3-turn coils without significant issues

- Fewer electrical shorts in recent coils during winding
- Minimize sharp edges in the mandrel to avoid short
- Jury still out for the 40-turn coils
  - Need C3 mandrels to test wind



short winding video

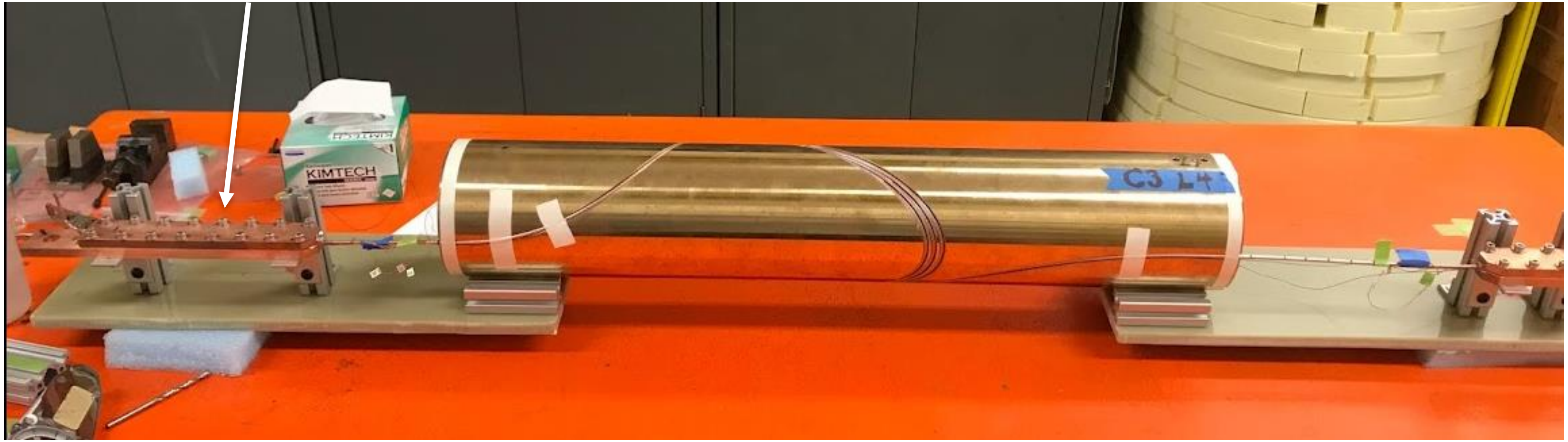
Degradation occurred; still need to be careful when handling the wire

Layer	After winding	After Stycast	Change
1	78%	76%	-2%
2	79%	65%	-14%
3	82%	80%	-2%
4	82%	77%	-5%
2b	73%	72%	-1%

- Difficult to understand why and where the degradation occurred with the voltage-tap signal

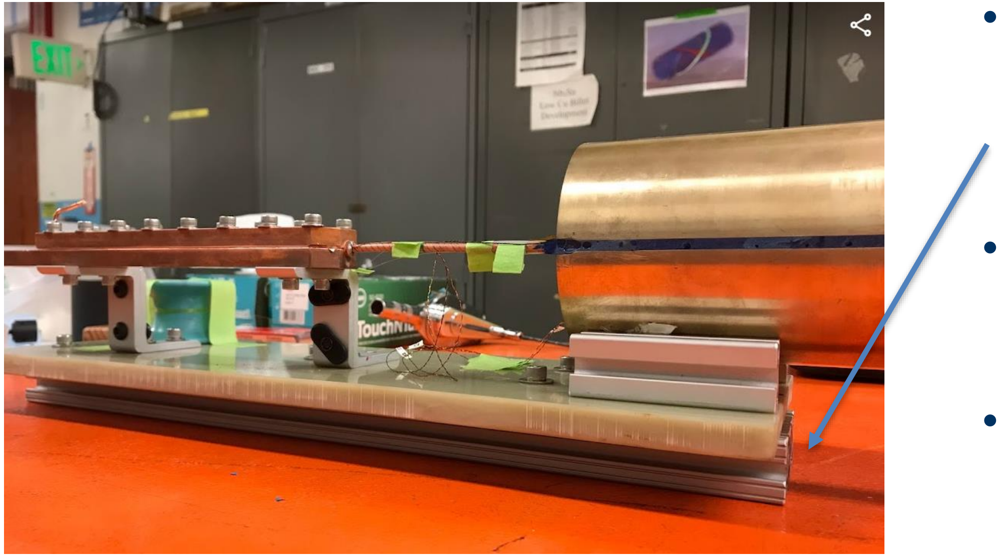
Earlier procedure could have strained the wire

- Wires were constrained in the termination clamps during the Stycast operation and test preparation



- G10 board flexing → strained and degraded the wire?

Addressing it following Seinfeld’s advice



- Strengthened the G10 board with an aluminum strongback. Decouple before cooldown
- Remove the wire from the clamps during the stycast operation
- Layer 2b with the new procedure looks good

“If you're efficient, you're doing it the wrong way. The right way is the hard way.” – Jerry Seinfeld. Hope he is right in this case.

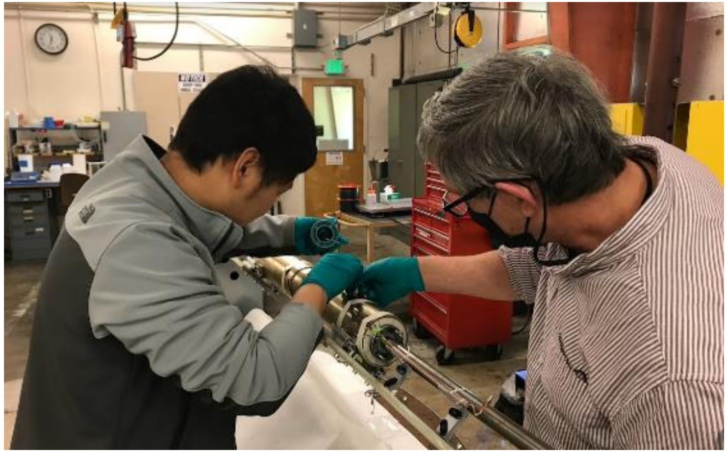
Learning how to use fiber to identify the locations of resistive voltage, a question that is still burning

- Heavily influenced by the pioneering SBIR work at Lupine

- Leveraging the lab expertise to learn faster

- Tried fibers with metal coating; did not observe obvious improvement in thermal contact yet

- Focus on the telecom-grade fiber, readily-available, 0.2 mm diameter

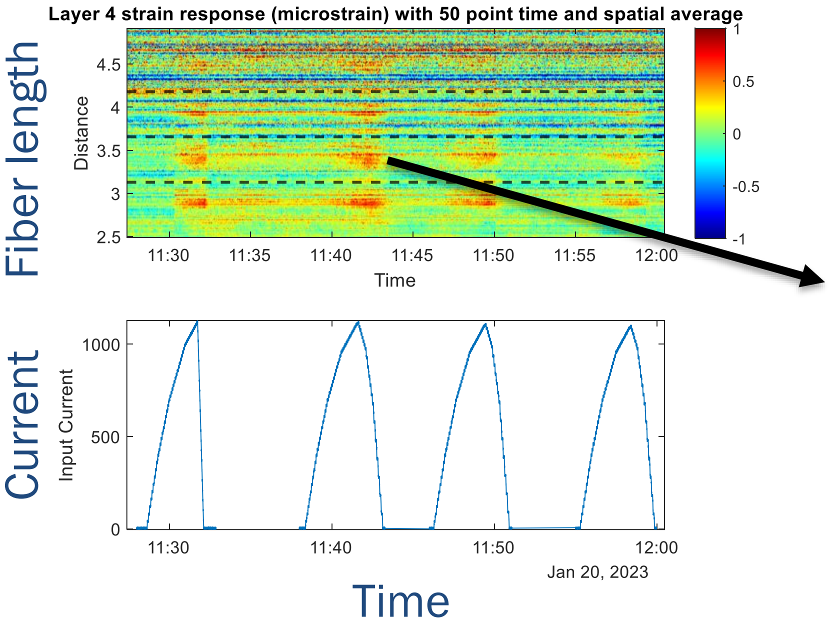


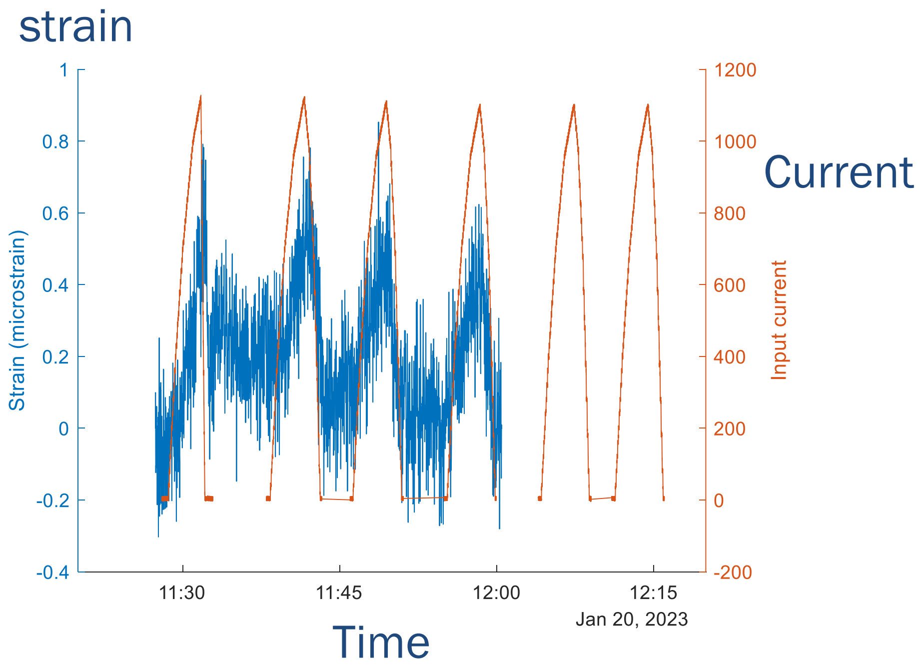
Not trivial to apply fiber

Fibers in Layers 3 and 4 recently gave interesting signals

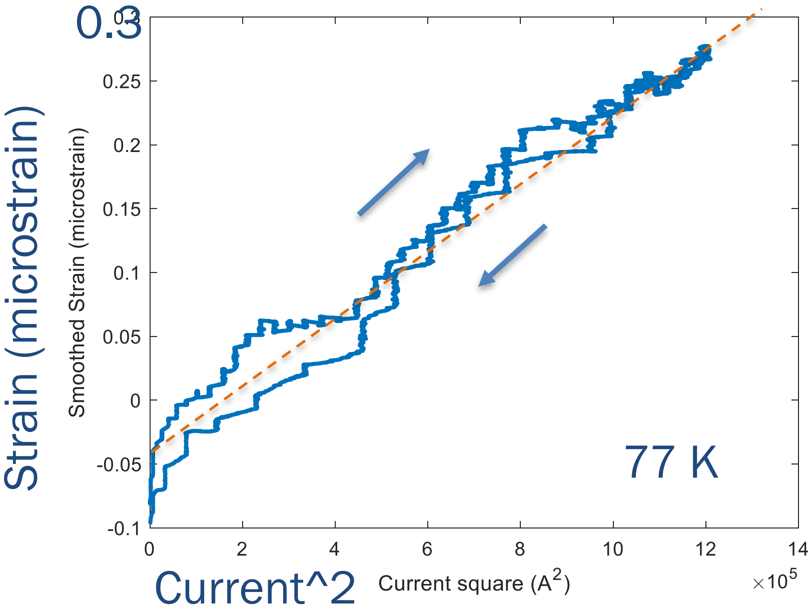
Layer 4, 77 K

L. Luo, LBL



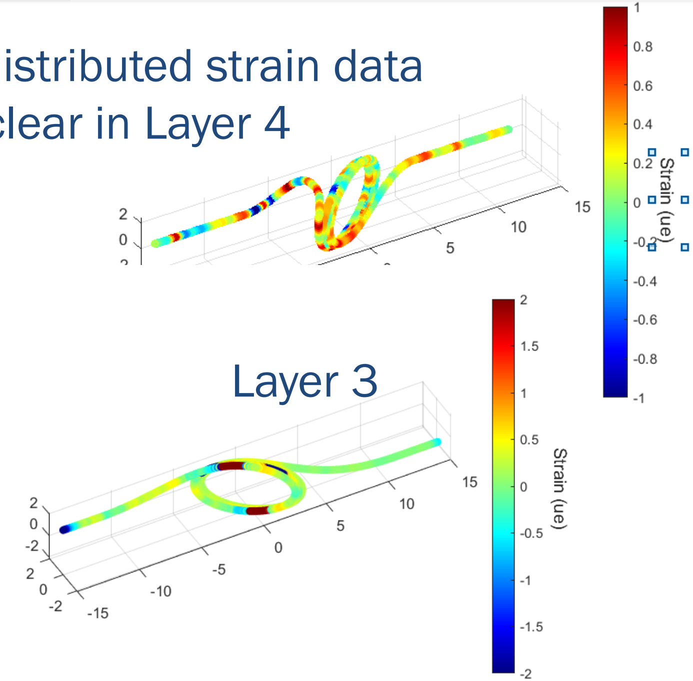


We interpret the signal as the strain on the wire due to the I x B force. Positive strain = tension on wire



- Hysteresis?

- The distributed strain data less clear in Layer 4



- Behavior at higher field and forces?
- Decouple temperature from strain?

Next steps in the fiber work

- Improve fiber installation
    - Reduce micro-bending in fiber, mold release?
- Seeking the lab resources to address the limitations of the commercial solution for superconducting magnet applications
    - Attenuation of light power
    - Large strain/temperature rate
    - Limited access to data acquisition and processing

“Let there be light”

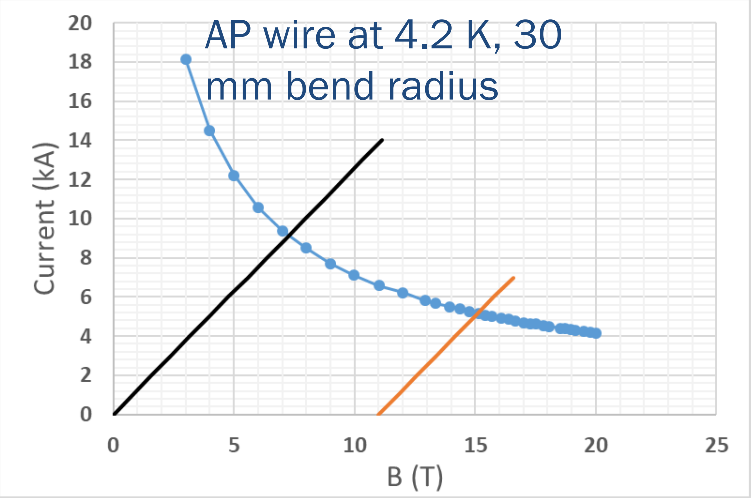
Beyond C3 – initial thoughts and conductor needs within next 18 months

- To generate a dipole field of 8 T
  - A stretch goal beyond 5 T
  - A stepping stone toward 10 T
  - To generate 5 T in 15 T background, the insert, stand-alone, generates *at least* 8 T

- Two options
  - OD < 120 mm, as an insert for CCT6
  - ID ~ 150 mm, relevant for a muon collider, 3 TeV c.o.m.

CCT option for the insert and the conductor need

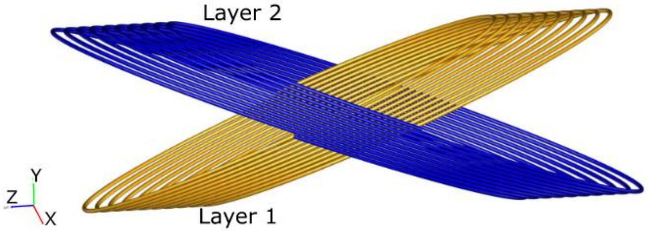
- 6-layer CCT
    - 45 mm ID, 118 mm OD
- 20 mm minimum bend radius
    - Recently demonstrated by ACT
- At the short-sample limit
    - 7 T stand-alone using the AP wire performance
    - The HM wire can bring it to 8 T
    - 4 T in background field of 11 T
- Total wire length 250 m, $1.2 M
    - 67% longer than C3 wire length

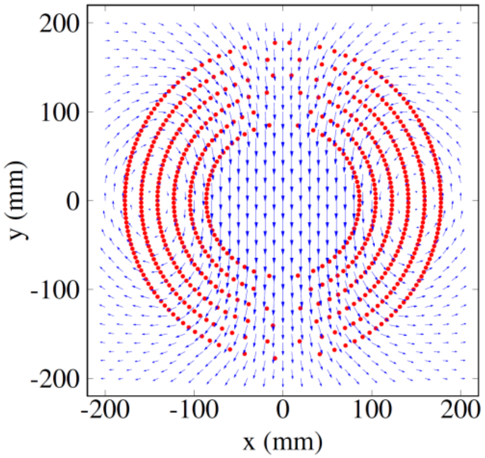


Engage and push the vendor

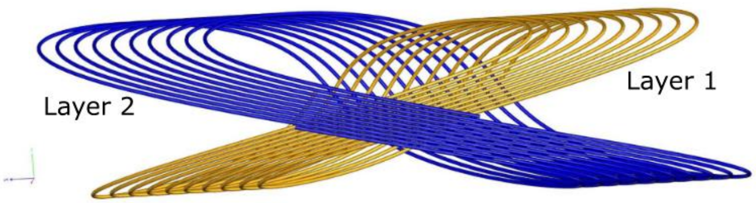
150-mm aperture magnets: dipole and combined-function magnets for muon collider

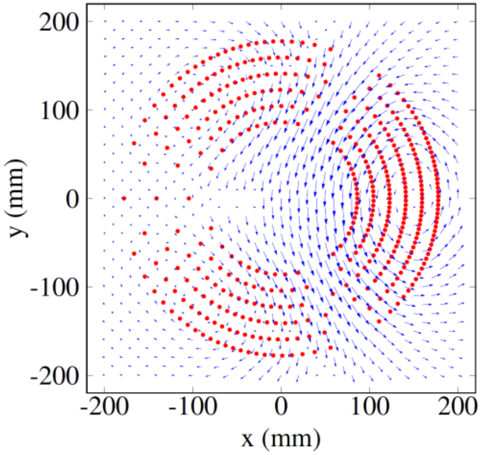
CCT dipole





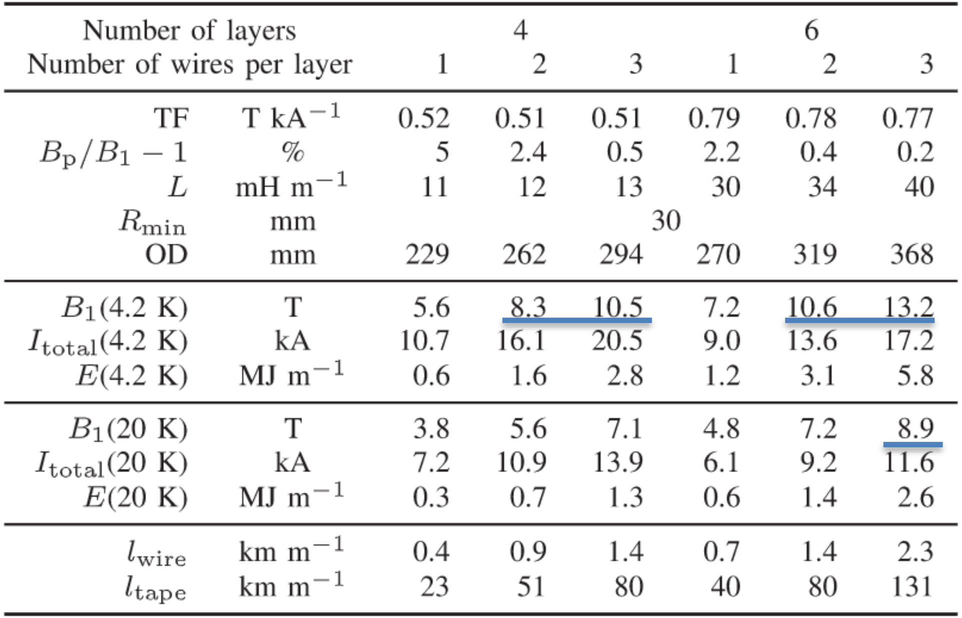
Dipole-quad combined function





[An initial look]

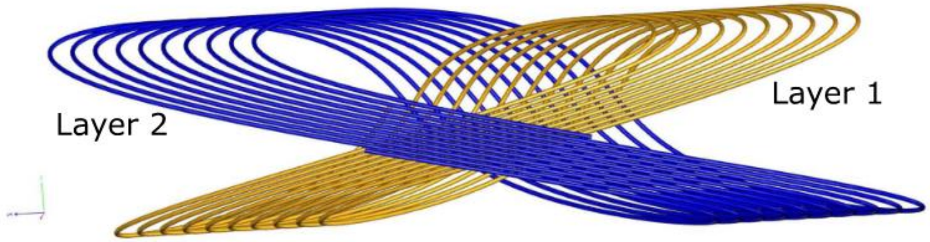
Several CCT options to use today’s CORC® wires to generate 8 T dipole field, at 20 K. But new experience is required



Number of layers		4			6		
Number of wires per layer		1	2	3	1	2	3
TF	T kA^{-1}	0.52	0.51	0.51	0.79	0.78	0.77
$B_p/B_1 - 1$	%	5	2.4	0.5	2.2	0.4	0.2
L	mH m^{-1}	11	12	13	30	34	40
R_{min}	mm	30					
OD	mm	229	262	294	270	319	368
B_1(4.2 K)	T	5.6	8.3	10.5	7.2	10.6	13.2
I_{total}(4.2 K)	kA	10.7	16.1	20.5	9.0	13.6	17.2
E(4.2 K)	MJ m^{-1}	0.6	1.6	2.8	1.2	3.1	5.8
B_1(20 K)	T	3.8	5.6	7.1	4.8	7.2	8.9
I_{total}(20 K)	kA	7.2	10.9	13.9	6.1	9.2	11.6
E(20 K)	MJ m^{-1}	0.3	0.7	1.3	0.6	1.4	2.6
l_{wire}	km m^{-1}	0.4	0.9	1.4	0.7	1.4	2.3
l_{tape}	km m^{-1}	23	51	80	40	80	131

- All require a ribbon of 2 – 3 CORC® wires
- Require new experience on magnet fabrication and performance
- Or better wires with a doubled or tripled current

In addition, winding may not be trivial for combined-function CCT magnet even with CORC® wires



- Combined-function magnets are needed to mitigate neutrino hotspots
- Elegant and also practical?

Pursue subscale models to dovetail a potential dedicated HTS magnet R&D for muon collider

- Can a ribbon-type cable with two CORC® wires work?
    - Make and test a 2-layer, 70 mm aperture magnet. 80 m CORC® AP wires, $ 320 k

- Can we wind a quadrupole or combined-function windings? What's the bending performance?
    - Wind and test 3-turn single-layer coils using single CORC® wire
    - Aperture 70 – 150 mm, 50 – 100 m CORC® AP wires, $ 200 – 400 k

Conductor needs for the uni-layer design?

- José Luis introduced the intriguing concept yesterday
  - Strong potential for both the insert and stand-alone magnet options

- Would be useful to make a sub-scale model soon to learn

- How much conductor do we need for insert and large-aperture models?

We study STAR® wires to keep conductor options open

- Next step is S1 magnet, a longer version of s0,
  - 2 layers, 40 turns, 2-wire ribbon cable, 1 – 2 T dipole field at 4.2 K
  - Can fit inside CCT5 as an insert test
  - 90 m STAR® wires ordered, expected delivery in 2023
  - Work with FNAL to make an anticryostat for the 50 mm aperture

- Driving questions for S1
  - Can we make longer STAR® wires with uniform geometry and I_c?
  - Can we impregnate the bare STAR® wires?
  - How does the magnet perform? What further magnet and conductor development is needed?

We study cabling options of STAR® wires to keep options of the option open

- Develop 6-around-1 cable toward a magnet conductor
  - Transposed configuration
- Supported by an SBIR Phase II project with AMPeers
  - Leveraging the lab cabling infrastructure and expertise
  - Project will provide 10 m long cable to make a 3-turn magnet within the next 18 months. If successful, an order can follow

The crystal ball did not work well last year; let’s try again

Milestone	Description	Target
AIIb-M3	CORC® CCT to reach 5 T dipole field	~~9/2023~~ → 12/2024
AIIb-M4	Complete design study of a 8 T REBCO dipole magnet	~~12/2022~~ → 6/2024
AIIb-M6	REBCO insert to generate 1 T in 8 T field from CCT5	~~6/2024~~ → 6/2025
AIIb-M8	REBCO magnet to generate 8 T dipole field	~~3/2025~~ → 6/2026

The Crystal Ball by John William Waterhouse (1902)

Recap and action items

- C3a is providing excellent learning opportunities on C3 fabrication and conductor behavior

- Immediate needs to make C3
    - Keep the door open for key staff, May 2023
    - Secure $85 k to machine C3 mandrels, July 2023
    - Complete and test C3a, September 2023

- Get to 8 T is a critical next step, assuming we reach 5 T next year
    - Secure funding to order wires for the next magnet within 12 months

One final remark on the REBCO Working Group

- The WG is working well
  - We have been meeting biweekly for three years, exchanging latest test results, ideas
  - An effective forum for further collaboration and collective learning
  - We certainly miss the voices of ASC

- Rotating the role of REBCO lead among interested labs
  - Can further enhance the WG and collaboration