# Prospects of ReBCO Cables in Future High-field Accelerator Magnets

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# Food for Thought

- There is a large investment on the development of the ReBCO (HTS) cable from the private investors for fusion industry.
- Current HTS wire and HTS cable market (and hence development of the HTS cables) is primarily driven by the privately funded fusion industry; and is likely to remain so for a foreseeable future.
- Several decades ago, private MRI industry benefitted from the development of NbTi superconductors from a large investment from the government agencies on the accelerator magnet R&D.
- Now, can the accelerator magnet community draw similar benefit from the development of the ReBCO cable from an unprecedented funding from the private investors on the fusion R&D?

# Viability of ReBCO for Accelerator Magnets?

**This presentation is primarily for dipoles and quadrupoles even though muon colliders need solenoids also**

## ReBCO comes in tape form and that poses several challenges:

- A local defect, not always detected at 77 K QA test of conductor of ReBCO, could cause an irrecoverable damage to the accelerator magnet coils, when operated at high fields and/or high stresses. This challenge is faced in fusion magnets as well.
- Tape conductors (rather than round wire) create field errors that may be too large for accelerator magnets. Similarly, tape conductors cause large losses that may be too much for fusion devices.
- Quench protection of the large high stored energy HTS magnets is a major issue for the accelerator magnets. This is also a major issue for the large fusion devices.

## High current HTS cables are essential to deal with the above issues.

- Will that and other development in technologies be sufficient? Fusion community has made a massive investment and is counting on developing a reliable solution.
- Can/should accelerator community partially align its program to benefit from above?

# Emphasizing the Similarities

- Accelerator magnets and fusion applications both need coupled tapes (wires) either to reduces losses or to reduce field errors.
- Both applications need high current ReBCO cables.
- Both applications need significantly longer length cables with more uniform performance along the length.
- Both need the prices of the HTS cable to go down by a large amount to make the devices being developed viable.

# Pointing the Differences and Possible Path Forward

The conventional magnet designs need HTS cables that can be bent in small bend radii; fusion cables typically don’t require that.

- Can a relatively small strategic investment leverage the development of the cables that can be bent in small radii with a little to no loss in the full potential of REBCO?

**------------ AND/OR ------------**

- Can accelerator community make some financial and intellectual investment in developing magnet designs that can use cables developed for fusion, despite them having large bend radii?

# ReBCO Cable Designs

# Examples of Some ReBCO Cables

| Cabling methods | Helical winding on a round former | | Stacking | |
|---|---|---|---|---|
| | Winding with a long pitch on a large diameter former. | Winding tightly with a short pitch on a small diameter former. | Roebel cabling of tapes cut in zigzag pattern. | Twisting stacked tapes. |
| |  |  |  |  |
| | | **CORC** Conductor on Round Core | **RACC** Roebel Assembled Coated Conductor | **TSTC** Twisted Stacked-Tape Cable |

M. Takayasu, et al, *Supercond. Sci. Technol.* 25, 014011, 2012.

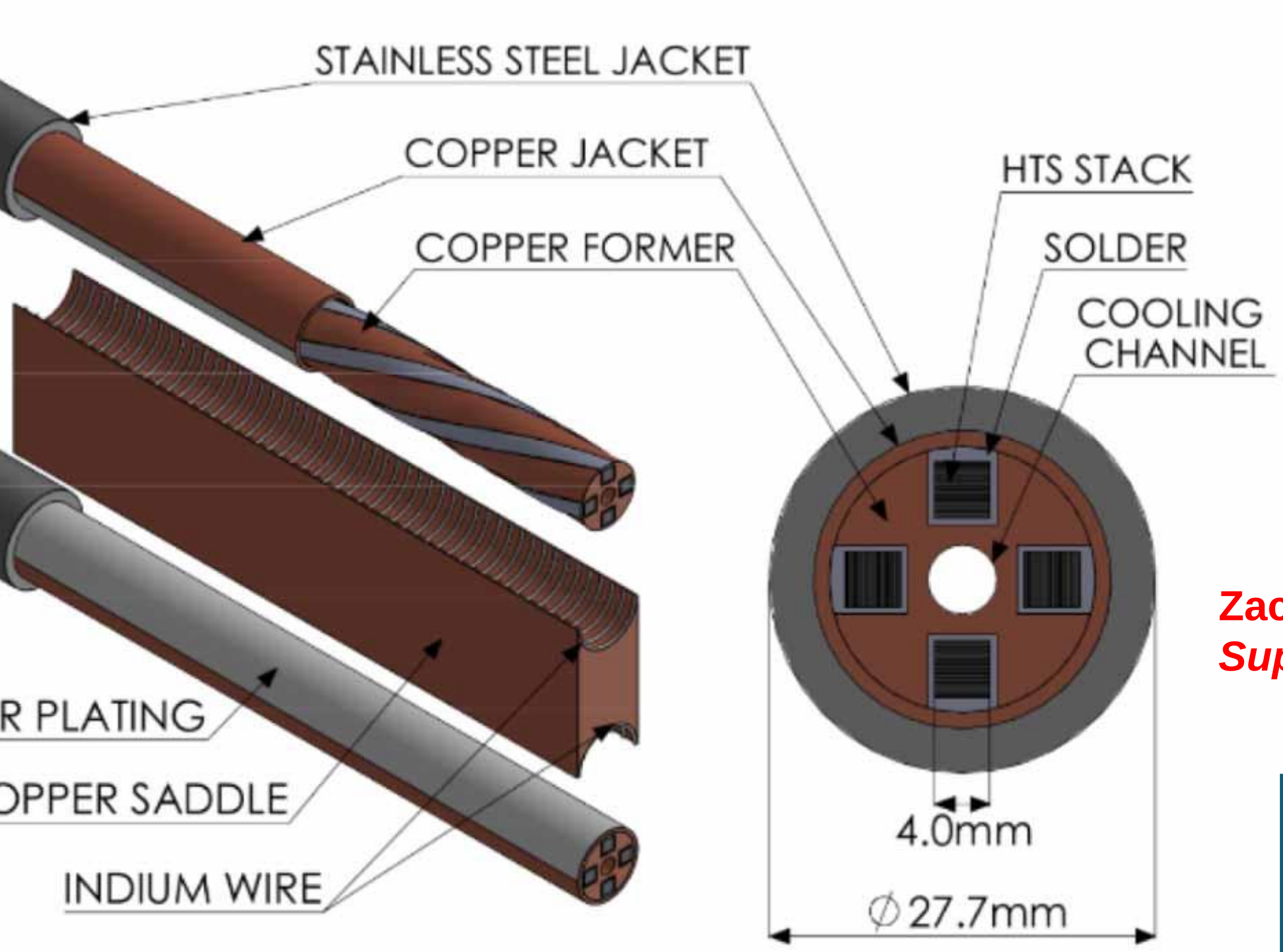
VIPER (next slide)

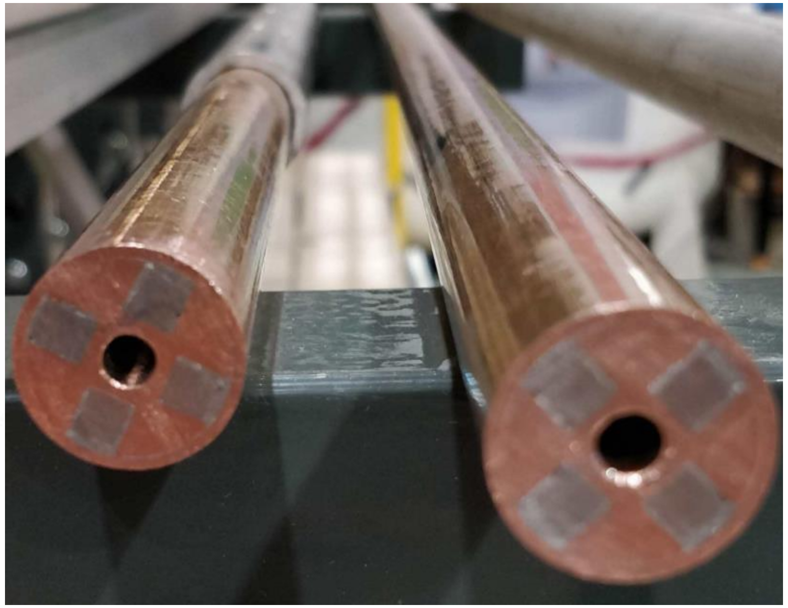
**STAR 6-around-1 cable**

Courtesy: V. Selvamanickam

# VIPER cable for fusion by MIT and CFS

SPARC



**Zachary S Hartwig *et al* 2020**
***Supercond. Sci. Technol.* 33 11LT01**

**Needs large bend radius (100 mm)**

# Possible VIPER Cable for Accelerator Magnets

**Possible parameters of a VIPER cable with the present state of the art *:**

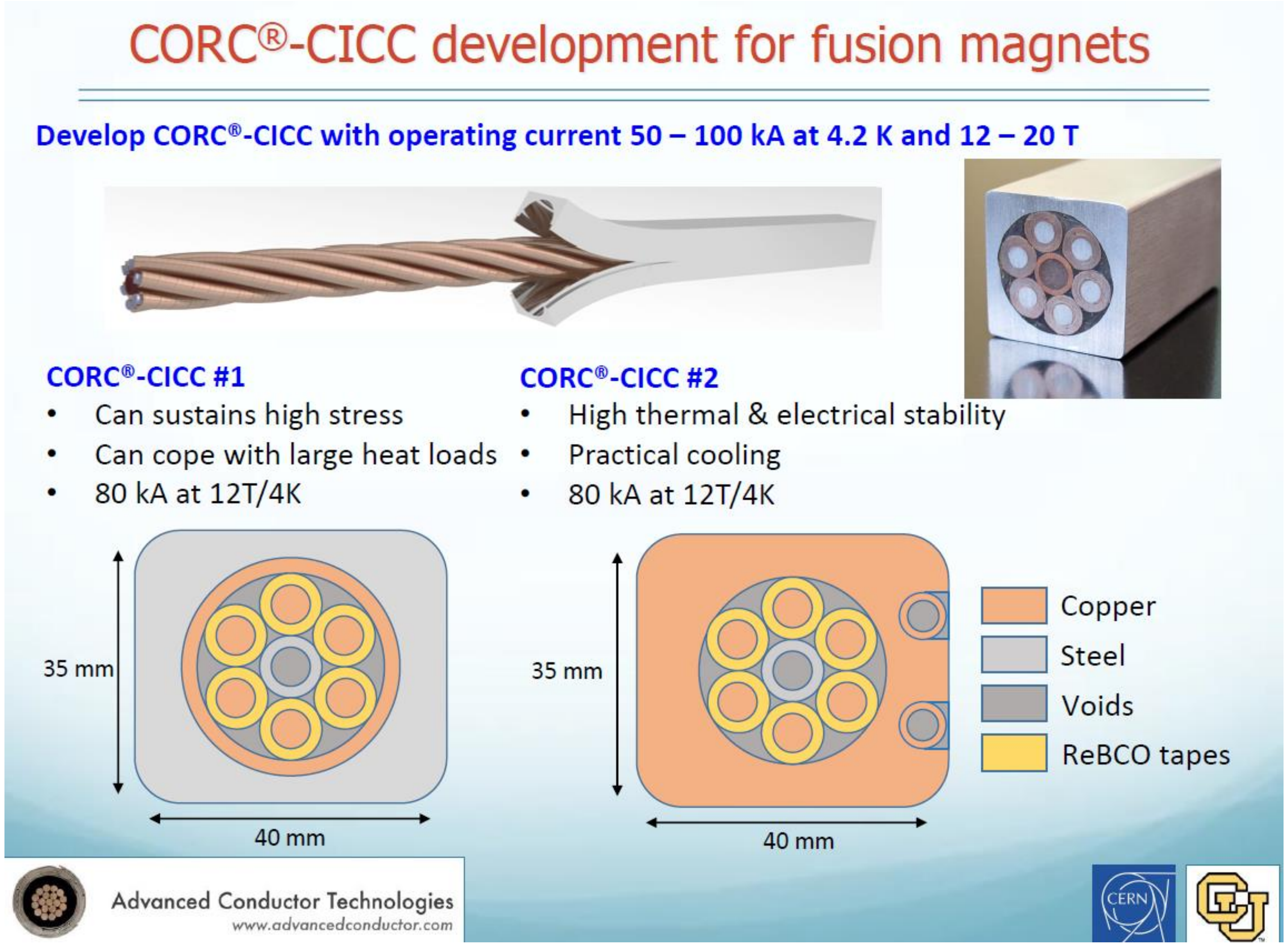
- **Cable $I_c$(20T, 4K) = 62 kA**
- **Cable $J_e$(20T, 4K) = 255 A/mm$^2$**
- **Cable $J_{cu}$(20T, 4K) = 420 A/mm$^2$**
- **Cable outer diameter = 16 mm**
- **Bending Radius = 100 mm**

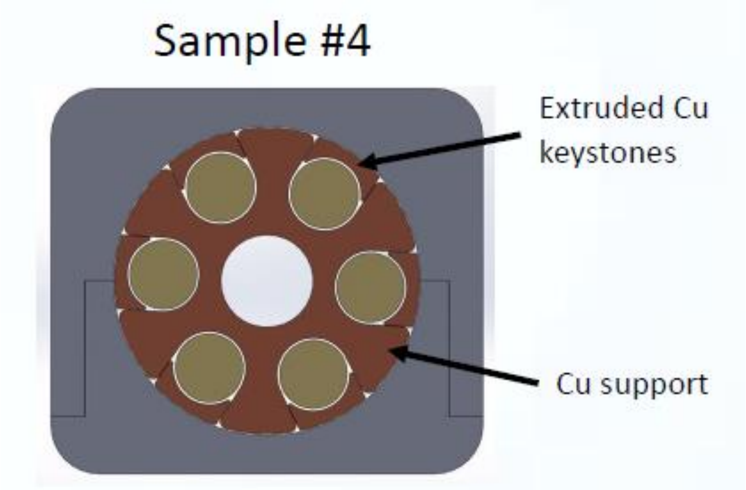
*Zachary Hartwig, Private communication

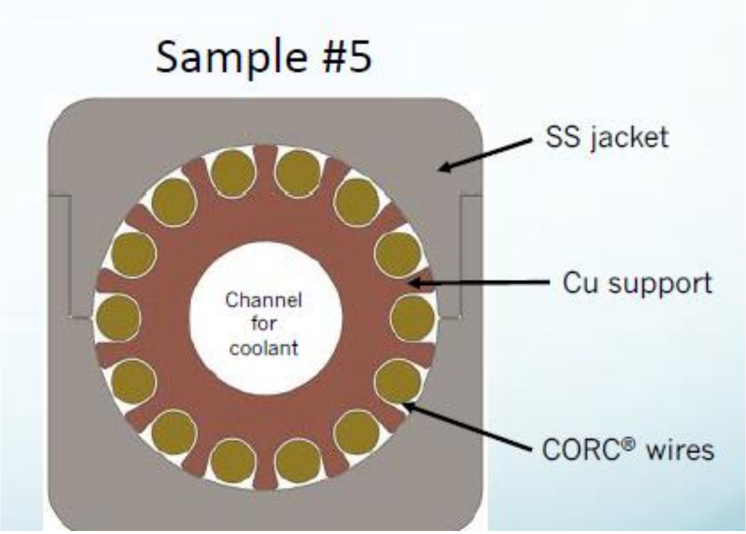
**A cable with a $J_e$(20T,4K) of 500-100 A/mm$^2$ may be possible within a few years. This option then becomes even more interesting for accelerator magnets**

# Example of Fusion Cables - CORC®

## (High current cables – requires larger bending radii)




Courtesy: Danko Vander Laan, ACT

# Example of Accelerator Cable - CORC®

## Case when bent in a relatively smaller bending radius

**CORC being used in canted cosine theta dipole (LBL/ACT Program)**


This work was in part supported by the US Department of Energy under agreement numbers DE-SC0009545, DE-SC0014009, DE-SC0015775 and DE-SC0018127.

**Recent progress on CORC®-based high-field magnet development**

Danko van der Laan and Jeremy Weiss
Advanced Conductor Technologies & University of Colorado, Boulder, Colorado, USA

Tim Mulder, Alexey Dudarev and Herman ten Kate
CERN, Geneva, Switzerland

H. Higley, S. O. Prestemon and X. Wang
Lawrence Berkeley National Laboratory, Berkeley, California, USA

U.P. Trociewitz, D. Abraimov, A. Francis, J. Gillman, D.S. Davis, Y. Kim, V. Griffin, G. Miller, H.W. Weijers, L.D. Cooley, and D.C. Larbalestier
National High Magnetic Field Laboratory, Tallahassee, Florida, USA

Ramesh Gupta
Brookhaven National Laboratory, Upton New York, USA

Advanced Conductor Technologies
www.advancedconductor.com

LTSW 2020, Berkeley, CA, February 28, 2020

### Higher current cable (particularly when the bend radius can be larger)

- CORC wires (30 tapes, 3.7 mm thick overall): Je(20 T) 400 - 450 A/mm2 (Ic 4,500 - 5000 A)
- CORC cables (42 tapes, 6.8 mm thick overall): Je(20 T) 600 A/mm2 (Ic 20,000 A)

Courtesy: Danko Vander Laan, ACT

# STAR Wires for Accelerator Magnets

AMPeers

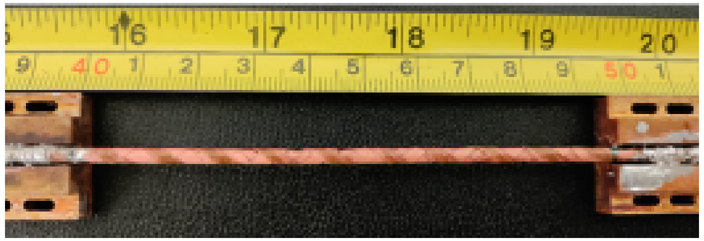
UNIVERSITY of HOUSTON

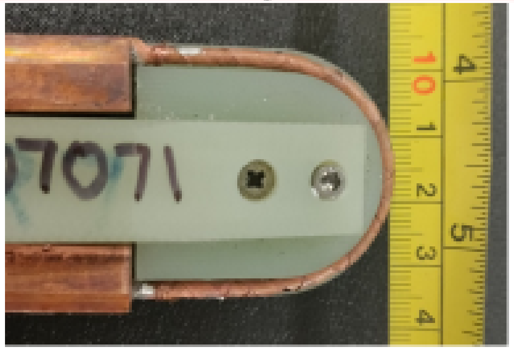
## $J_e$ > 1,000 A/mm² at 4.2 K, 20 T with STAR® wires made with high $I_c$ Advanced MOCVD REBCO tape strands

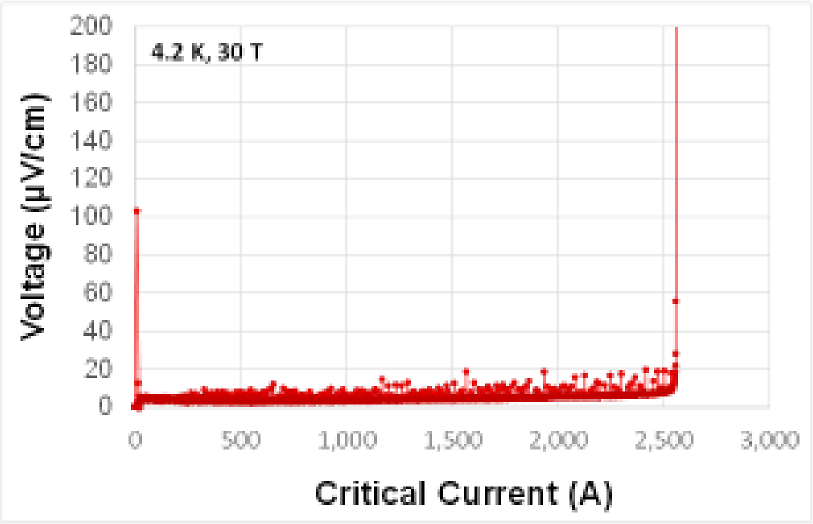
- 2.52 mm diameter STAR® wire on 0.81 mm former (12 symmetric tape strands)
- $I_c$ in straight form = **1140 A** at 77 K, self-field
- $I_c$ when bent to 15 mm radius = **1090 A** at 77 K, self-field (**95% retention**)
- Lift factor of tape used in wire = 4.72 at 4.2 K, 20 T
- Expected $I_c$ of 2.52 mm STAR® wire at 4.2 K, 20 T = **5,140 A (at 15 mm bend radius) → $J_e$ = 1,030 A/mm²**
- STAR wire quenched at 2550 A @ 4.2 K, 30 T; $J_e$ > 500 A/mm²

Courtesy:
Venkat Selvamanickam

Can be bent in small bend radii







# STAR Cables for Accelerator Magnets

AMPeers

UNIVERSITY of HOUSTON

Courtesy: Venkat Selvamanickam

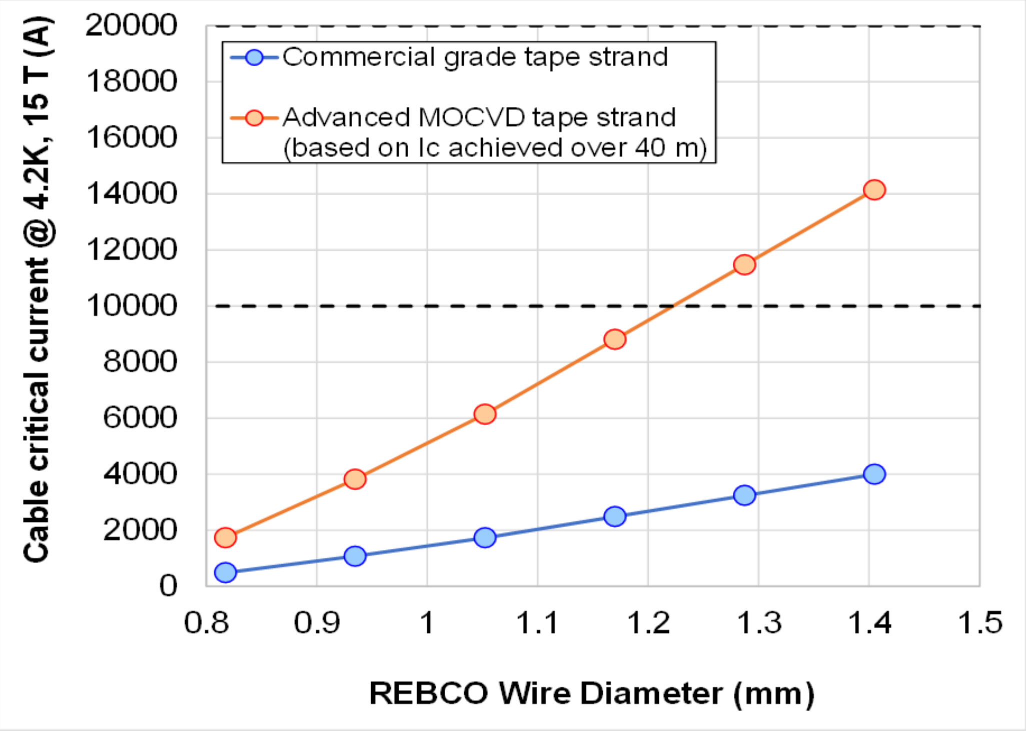
**2-m-long, 5.6 mm diameter 6-around-1 cable demonstrated by LBNL with 6 STAR® wires (1.8 ± 0.1 mm diameter)**

*$I_c$ of compact multi-strand STAR® cable = 1,444 A at 77 K, self-field*
*→ 80% of sum of $I_c$ of individual STAR® wires*

BERKELEY LAB

U.S. MAGNET DEVELOPMENT PROGRAM

4 mm diameter STAR® cable targeted with six 1.3 mm diameter STAR® wires with Advanced MOCVD tape strands




**Higher current for moderate bend radius cable.**
**Even higher current may be possible for larger bend radius.**

***10 kA at 4.2 K, 15 T** achievable with 4 mm diameter STAR® cables at targeted 25 mm cable bend radius.*

# Other ReBCO Cable Possibilities in Early Stages

ExoCable technology

Brookhaven Technology Group

**Courtesy:**
**Vyacheslav Solovyov**


## Defects and Defect Tolerance of 2G cables


Vyacheslav Solovyov[1], Ramesh Gupta[2], William Sampson[2], Anis Ben Yahia[2] , Makoto Takayasu[3] and Paul Farrell[1]

[1]Brookhaven Technology Group Inc., Stony Brook, NY 11794

www.brookhaventech.com

[2]Brookhaven National Laboratory, Upton, NY 11973

[3]Massachussets Institute for Technology, Cambridge, MA 11794

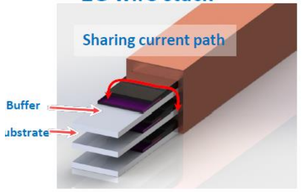


Supported by U.S. DOE Office of Science awards DE-SC0018737 and DE-SC0020832

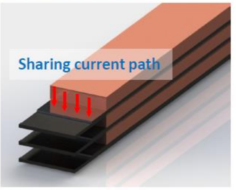

## Defect—tolerant, low AC loss cable

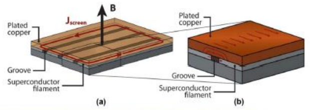
- Single-filament magnets proven difficult to protect against burnout
- Substrate prevents efficient current sharing, especially in narrow, low AC loss cables
- Multifilamentary cable is far more expensive than a single tape

2G wire stack




BTG exfoliated filament stack





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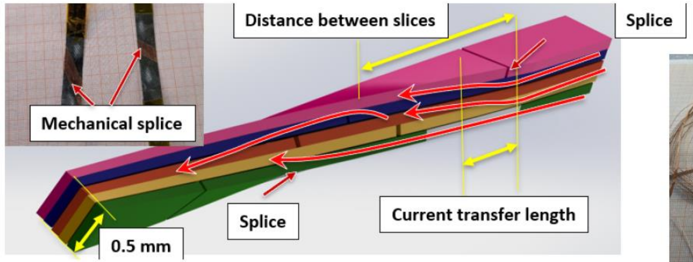
## Infinite length, splice-free narrow cable




20 0.5 mm filaments

- Human handling < 1 mm filaments is next to impossible
- Only wide, 10-12 mm tape is spliced and handled

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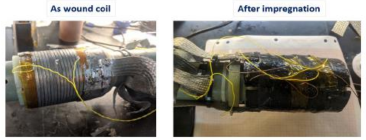
## Demonstration coil: 4 filaments, layer wound, break in each filament




Demo coil:
- 5 meters of 2 mm 4 filament cable
- Each filament has a break
- 10 cm ID

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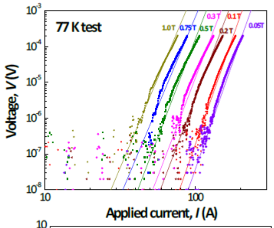
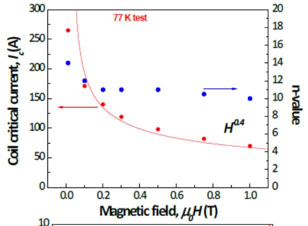
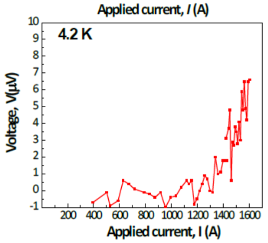
## Demo coil test at 77 K and 4.2 K

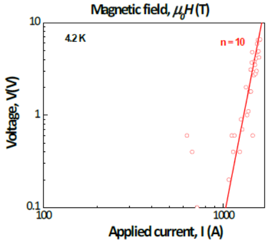
77 K




4.2 K




- The coil sustained 1,600 A at 4.2 K, $R < 1$ nΩ
- The n-value is limited by the discontinuities

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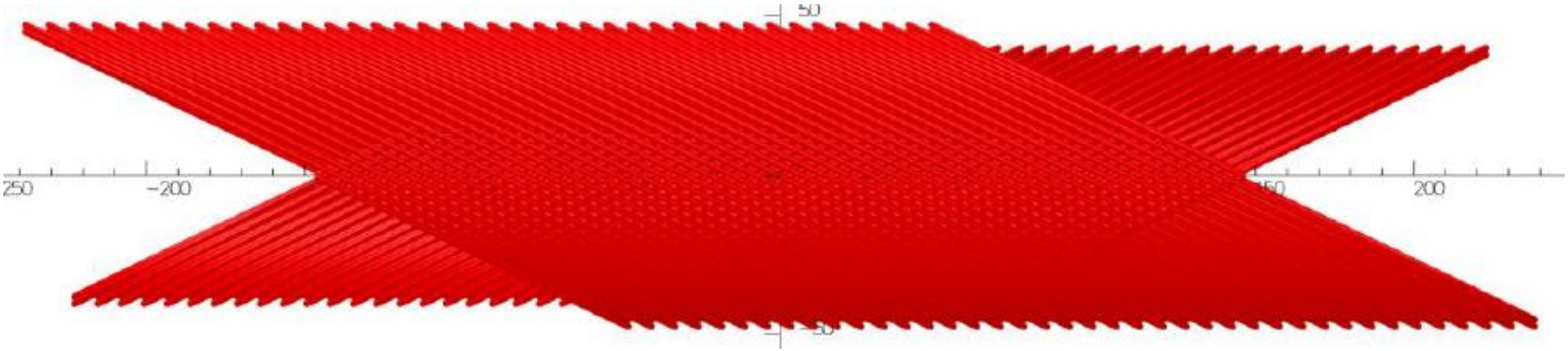
# Accelerator Magnet Designs

# General Considerations

- Several accelerator magnet coils have been made with the ReBCO tapes. Similarly, a few field hybrid dipoles, such as the 12.3 T hybrid R&D dipole at BNL was made with ReBCO tape and $Nb_3Sn$ cable.
- However, ReBCO cable, rather than the single tape, is desired.
- ReBCO cable R&D coils for accelerator magnets, that are being built with round cables, needs special consideration.
- The cable in these coils needs to be well supported and protected.
- Therefore, the structure becomes important part of the design. This, however, could significantly reduce the overall current density.
- Rectangular cables (including CICC) become an interesting possibility and are easier to use in designs those don’t require small bend radii.

# Canted Cosine Theta Designs with STAR and CORC@LBL

## Significant work at LBL on using ReBCO cables (STAR and CORC)




- Canted cosine theta design requires cable/wire to be bent in a small bend radius (~25 mm or so).
- It has been possible with some CORC and STAR wires and cables.
- However, degradation has been an issue.

Courtesy: Xiaorong Wang, LBNL

# MDP/LBNL is collaborating with industry to develop CCT dipole magnet technology CORC® wires



Courtesy: Xiaorong Wang, LBNL

- C1, two-layer design, reached 1.2 T
- C2, four-layer design, reached 2.9 T
- C3, six-layer design, under development, aiming at 5 T at 4.2 K
- Planning for the next magnet with a target field range 8 – 10 T

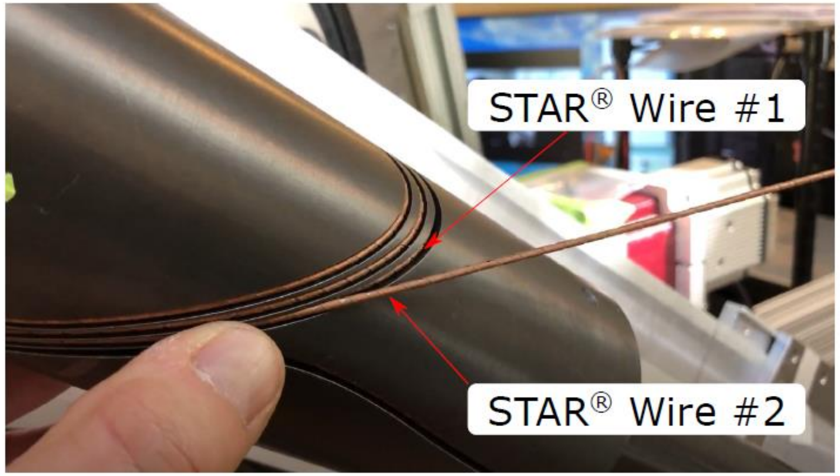
Advanced Conductor Technologies
www.advancedconductor.com

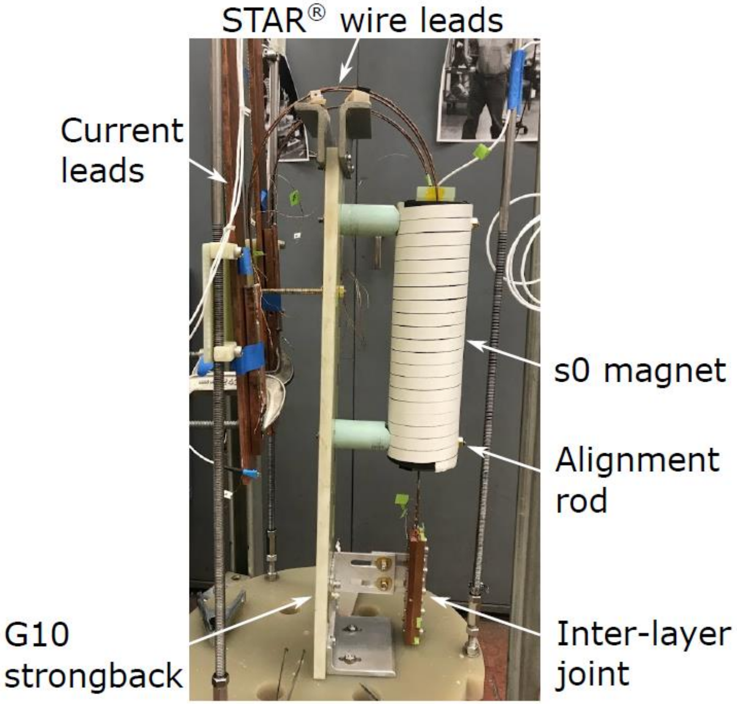
SuperPower Inc.
A Furukawa Company

NATIONAL HIGH MAGNETIC FIELD LABORATORY

# MDP/LBNL is collaborating with industry to develop CCT dipole magnet technology STAR® wires

AMPeers

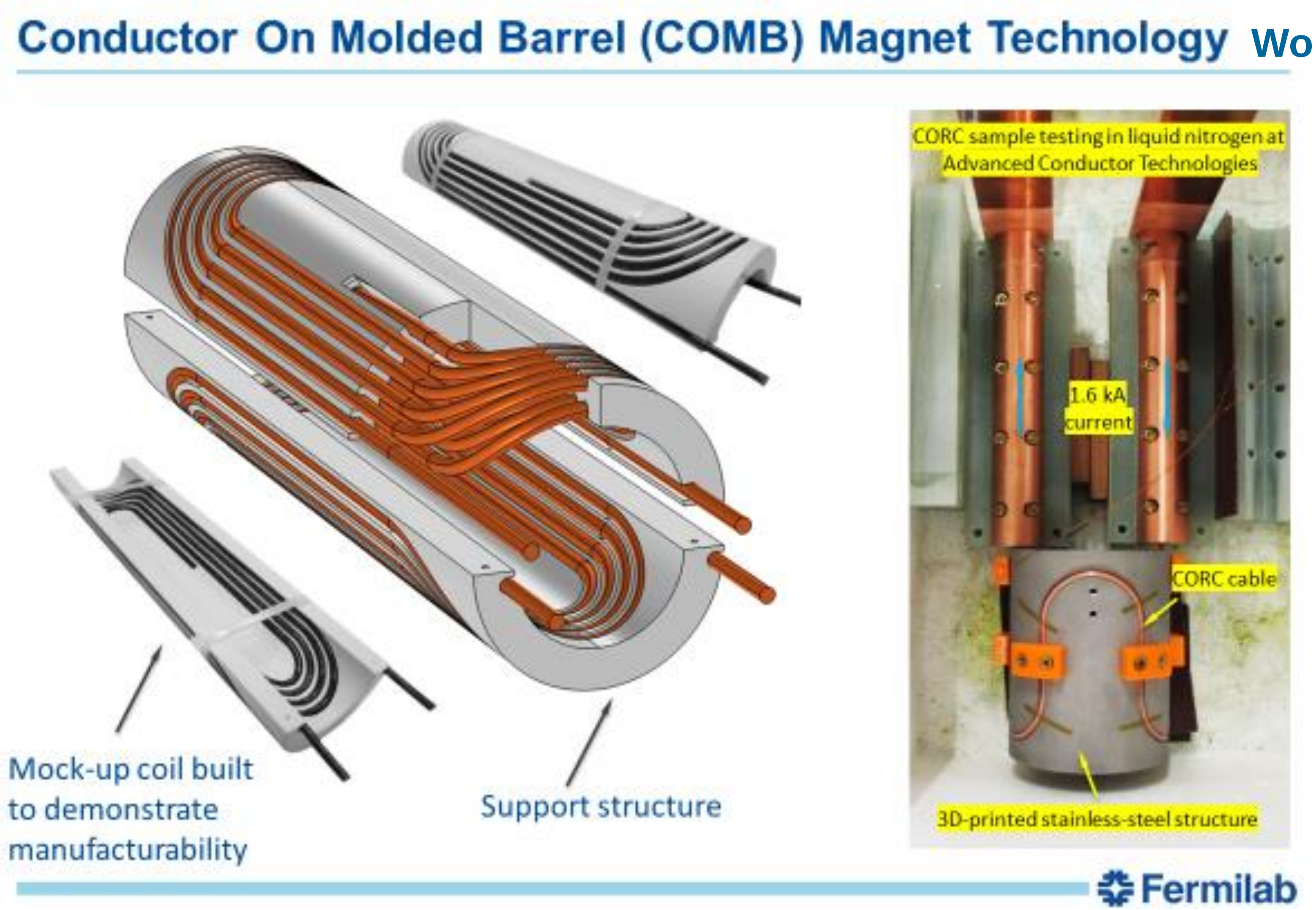


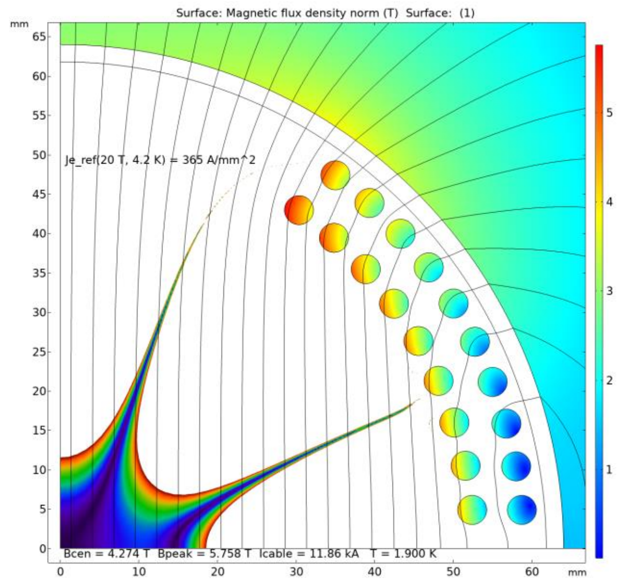



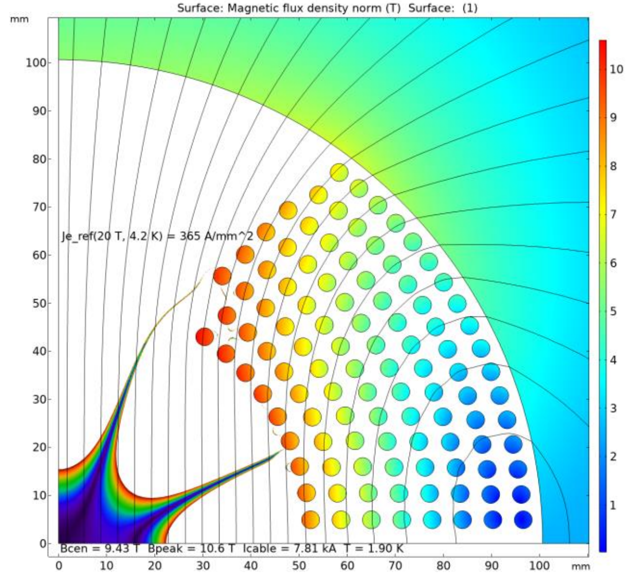

- Compact round wire, diameter approaching 1 mm
- Develop dipole magnets using multi-wire STAR® cable
- Developed a 3-turn subscale magnet using 2-wire ribbon-type cable. Next step, make and test a longer version

Courtesy: Xiaorong Wang, LBNL

# Work at Fermilab with CORC and STAR



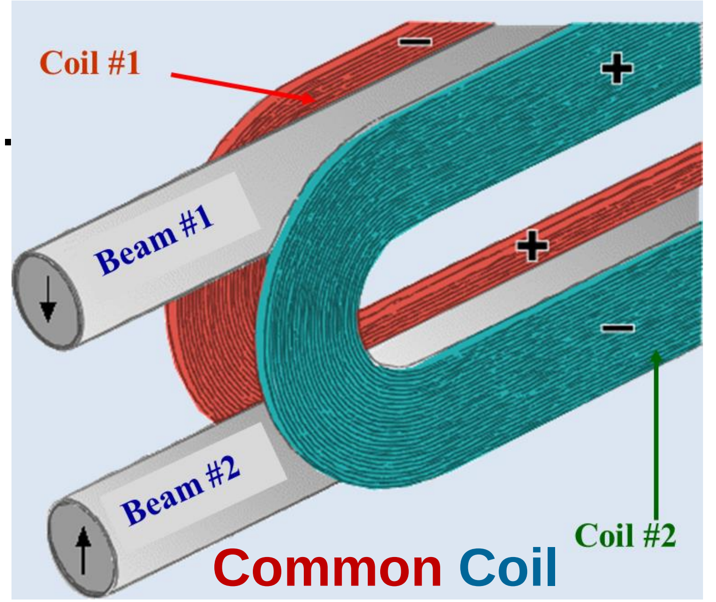




Courtesy:
V. Kashikhin
FNAL

- **Cable is placed inside a support structure.**
- **Scalable since forces are managed independently in each turn/layer.**
- **Requires cables/wires to have small bend radii.**

# Accelerator Magnet Designs Allowing Large Bend Radii

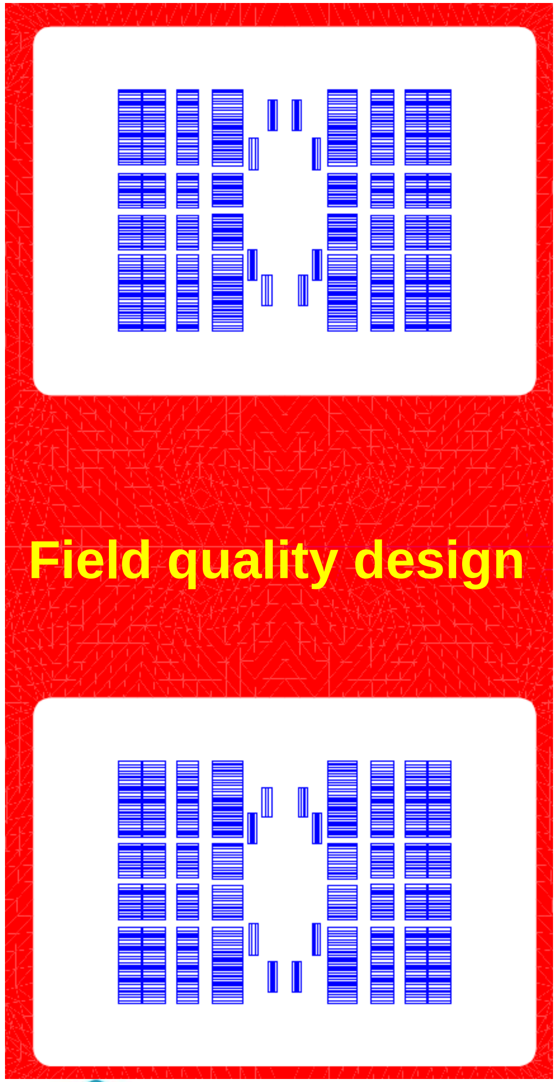
- Most accelerator magnet designs (such as cosine theta) need cables that can be bent in a relatively small bend radius (~25 mm).
- However, in the 2-in-1 common coil design, the required minimum bend radius of the cable depends on the separation between the two aperture (~100 mm or more), rather than the aperture itself.
- Similarly in the single aperture overpass/underpass (or cloverleaf) design, the required minimum bend radius is independent of the aperture. This minimum bend radius can be ~100 mm or more.
- High current fusion cables typically require large bend radii. Most of these cables can be adapted for use in the above two design.
- These designs facilitates using the fusion cables in accelerator magnets. However, they are yet to be fully demonstrated.
- If above can be done, then accelerator magnet community will directly benefit from the progress in fusion cable.



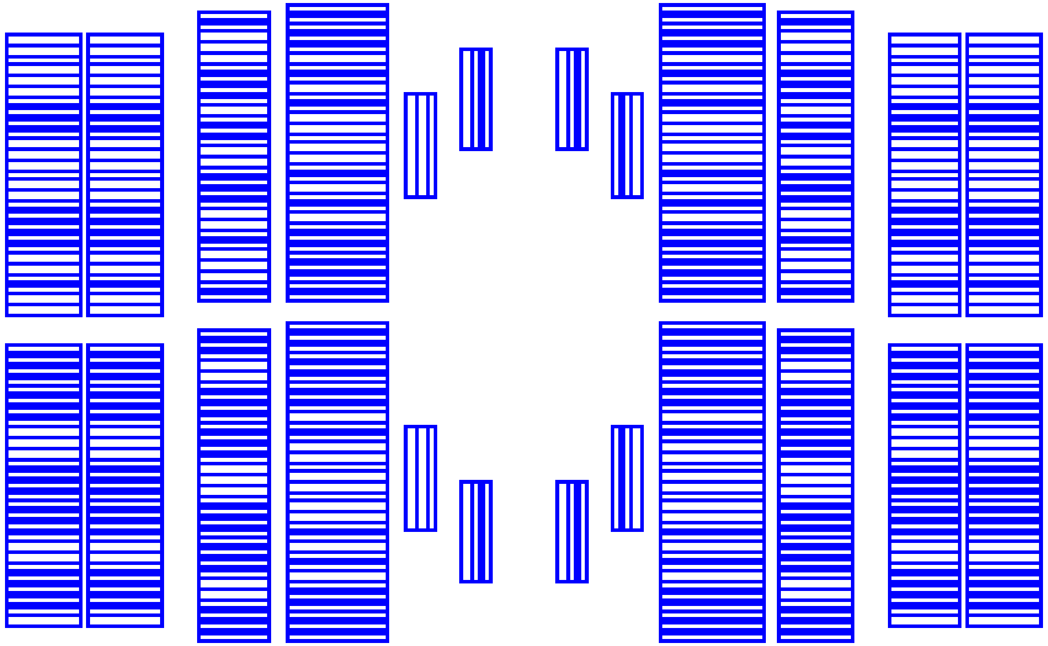

More on Thursday4LOr2A


**Need more designs that allow large bend radii for using the fusion cables**

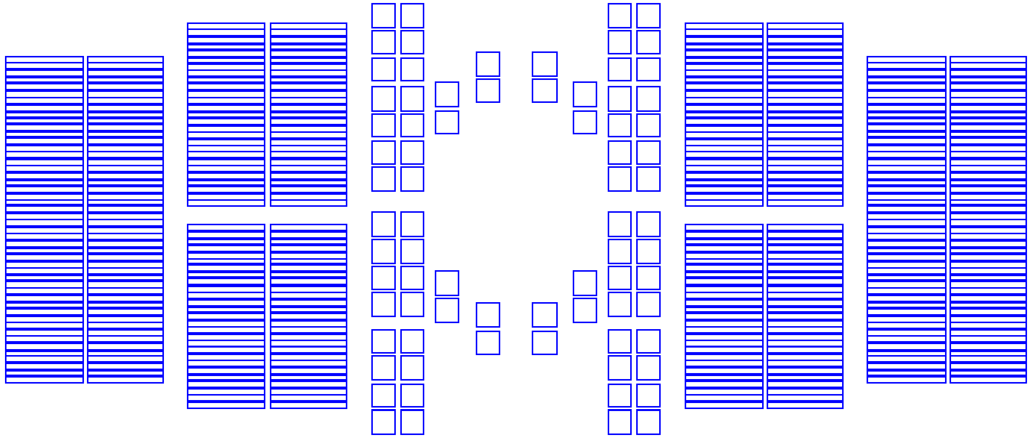
# 20 T HTS/LTS Hybrid Common Coil Design
## (these could be all HTS cable magnets)



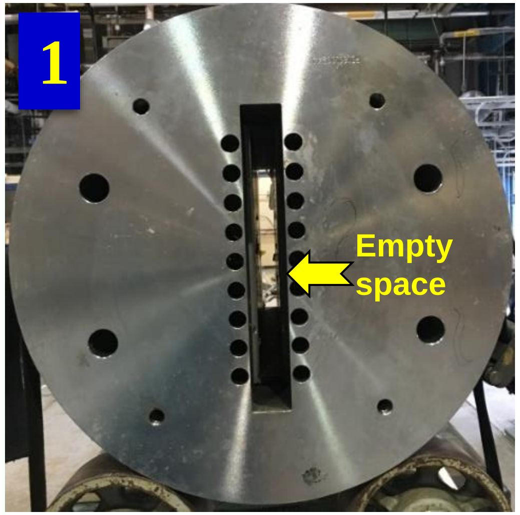

HTS coils could be made with Roebel or Rutherford cable (ReBCO or Bi2212)



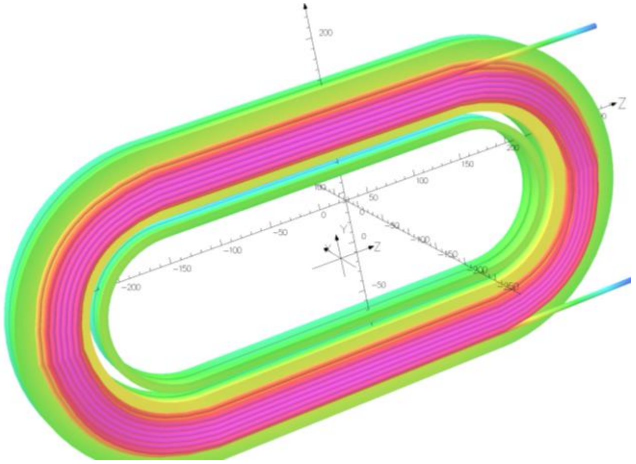
HTS coils could be made with VIPER or CORC® or CICC cable

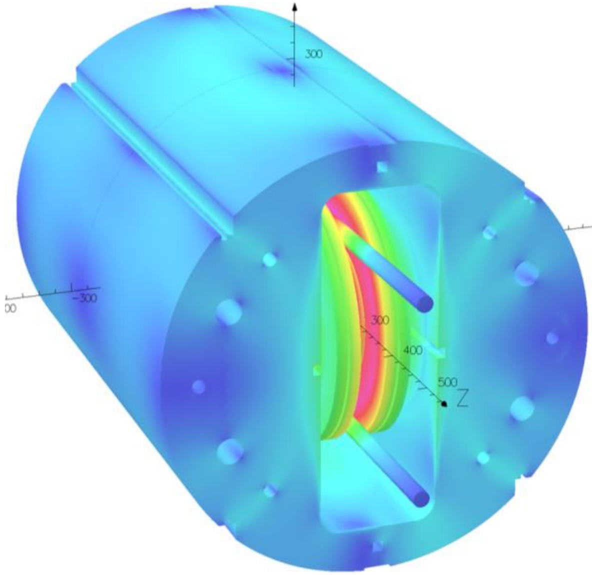


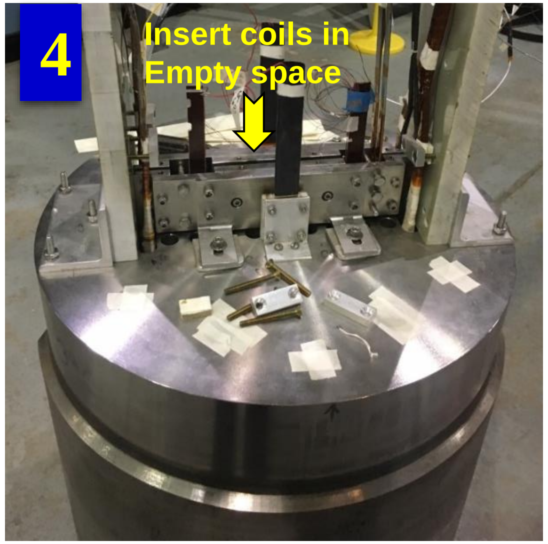
# Common Coil Program with ACT (MDP and STTR)

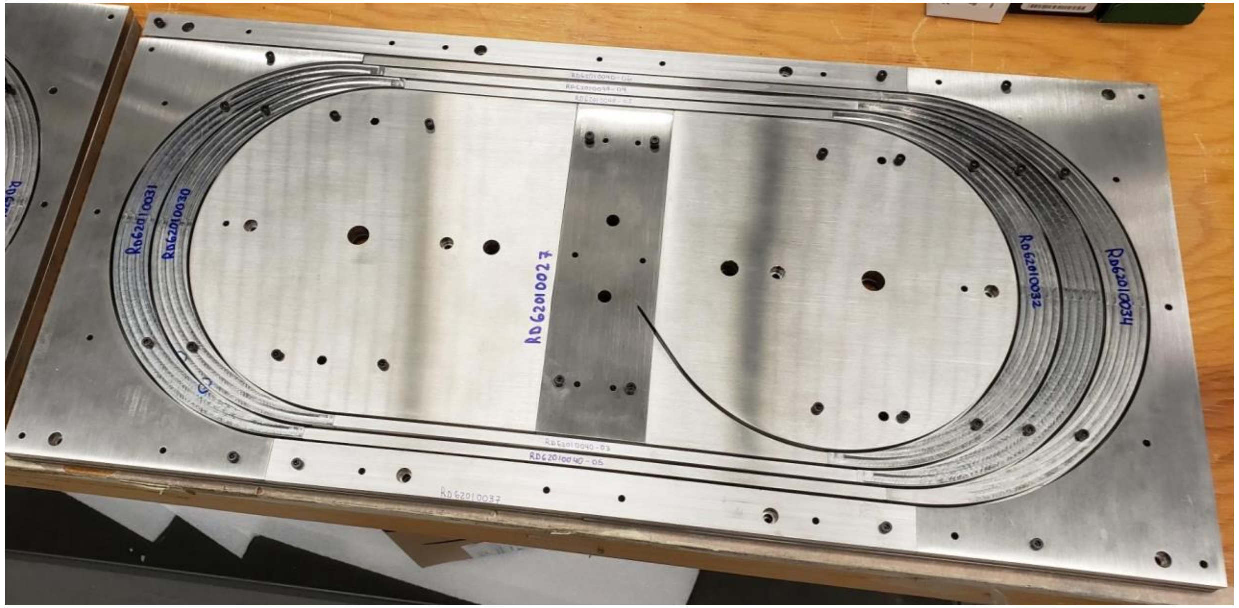




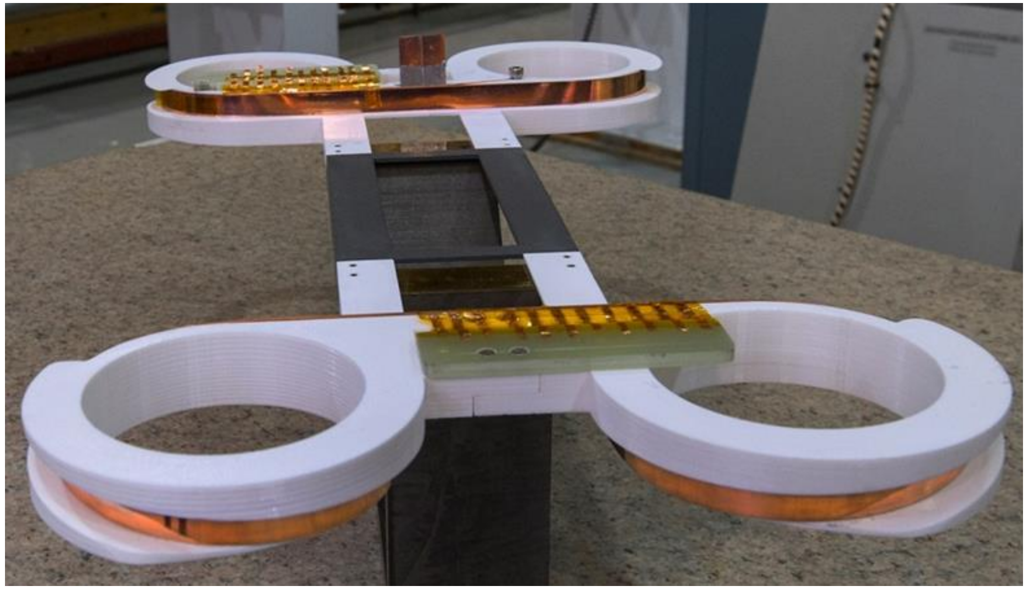


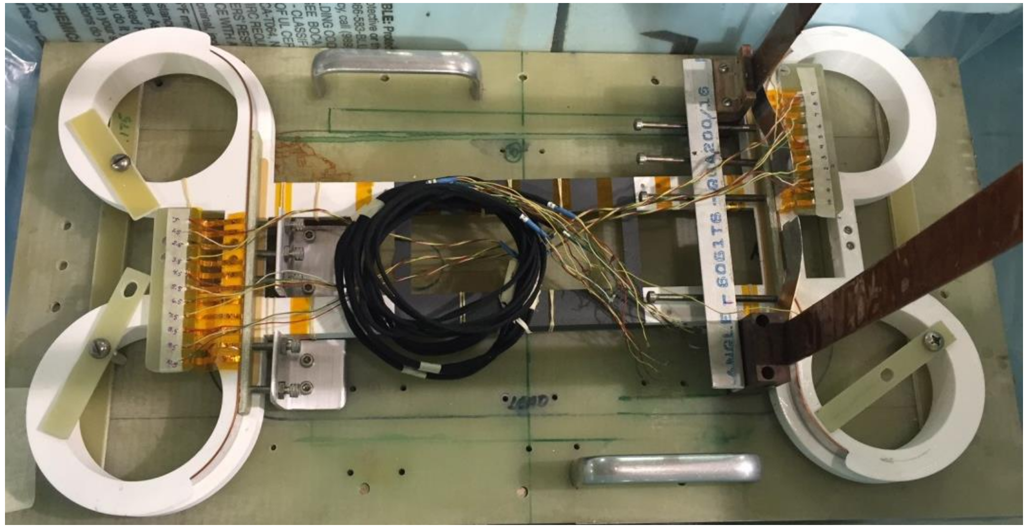


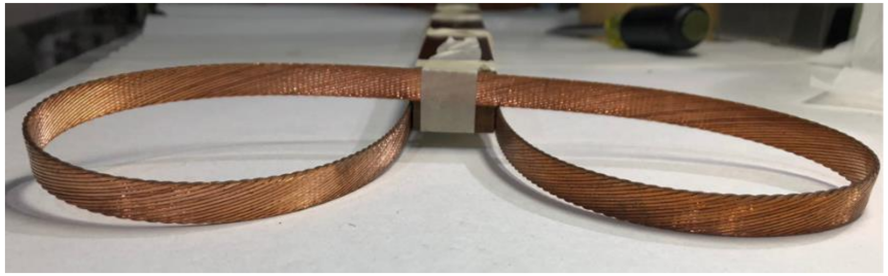



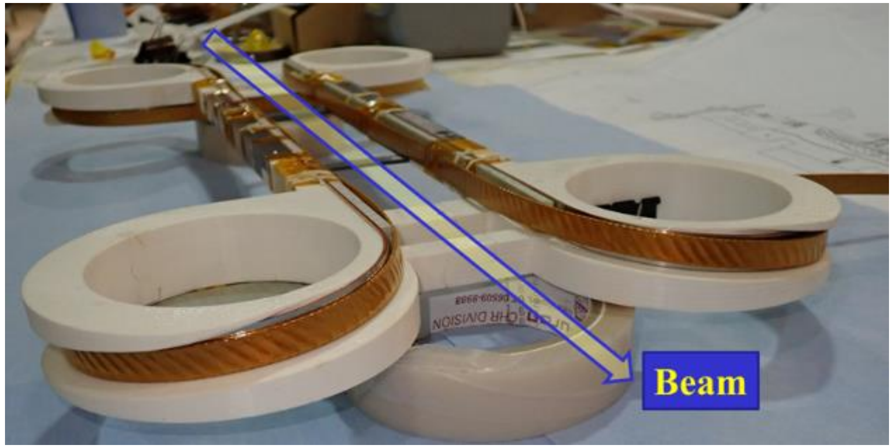
# OverPass/UnderPass SBIR Programs with e2P and PBL

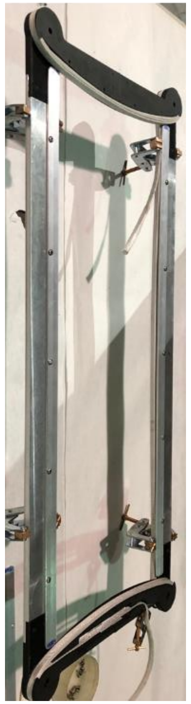




(with e2P using ReBCO tape)





(with PBL using $Nb_3Sn$ cable)

# A Dialogue Between Users and Manufacturers

**Challenge for accelerator magnet designers:**

- What can be done to develop and demonstrate new magnet designs that can allow the most efficient ReBCO cables as getting developed now? Example: magnet designs that can use large fusion cables.

**Challenge for ReBCO wire/cable manufacturers:**

- What can be done to modify cable architect (to the extent possible with incremental funding) to allow their use in a wide variety of magnet designs for accelerators? Example: cables that bends with small radii.

**Challenge for both to work jointly to improve the end-product:**

- What can be done to find integrated solutions to develop cable and magnet designs together? Examples: dealing with large stresses (CICC?), internal cooling (hole in the middle?), etc..

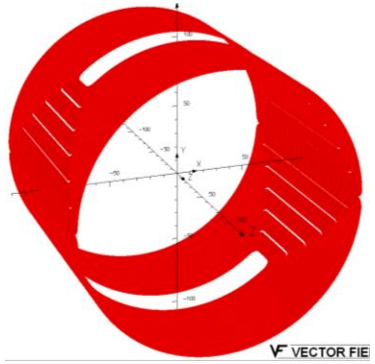
# Summary

- Most ReBCO coils for R&D accelerator magnets have so far been built with the HTS tapes. However, magnets with large stored energies will benefit from the HTS cables.
- High current HTS cables offer new opportunities, as well as new challenges.
- Current HTS cable market (and hence development of most HTS cables) is primarily driven by fusion applications; and it is likely to remain so for a foreseeable future.
- Can accelerator magnet community learn to use these new high current fusion ReBCO cables that are being developed now, in designing accelerator magnets?
- If we can, then both accelerator and fusion technologies will benefit in many ways.
- Both communities need:
  - Uniformity of ReBCO cables along the length and lot to lot to improve
  - Length of ReBCO tape and cable to increase
  - Cost of ReBCO cable to reduce
  - Demonstration of the devices that can be made reliably and remain well protected

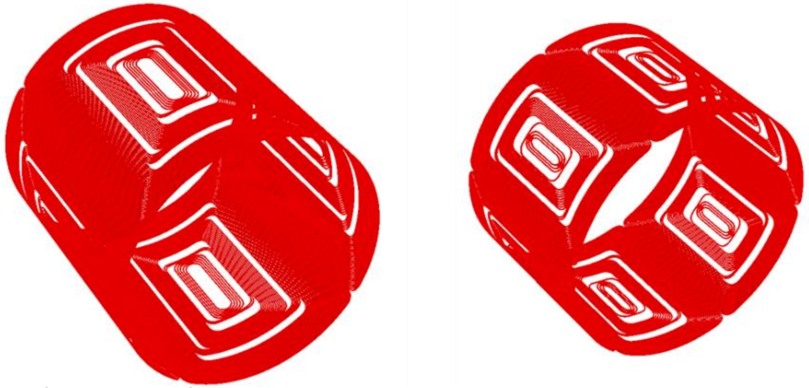
# Areas where accelerator magnet and fusion community can work together

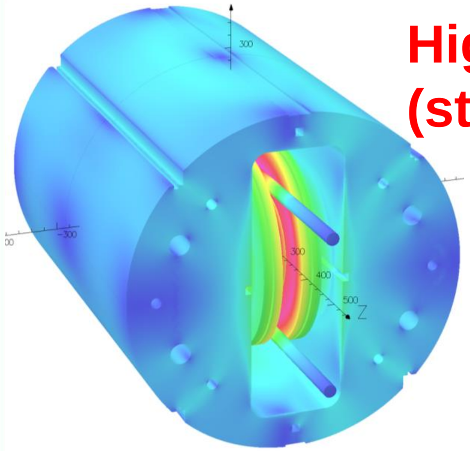
**There are a number of areas where accelerator magnet and fusion community can work together to develop technology collaboratively and benefit from a different ways of doing things beside the cables:**

- Quench protection of coils made with ReBCO cables
- Advanced detection and diagnostic technologies
- High current cable and coil test in background field
- Short length magnets (coil diameter/radius < length)



**Fusion needs some short magnets.**
Optimum integral design can make dipoles with length less than coil dia quadrupoles L < radius, sextupoles L < 2/3 radius, etc..





Fusion cable test at BNL in 10 T dipole field

**High current and high ramp rate cable testing (straight or bent and at various temperature)**