U.S. MAGNET DEVELOPMENT PROGRAM

Status of Bi-2212 CCT coil development and steps towards a 0.8 m long Bi-2212 CCT magnet for hybrid testing

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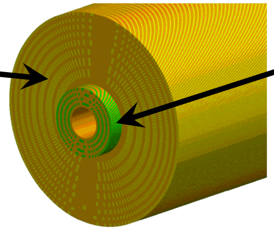
Outline

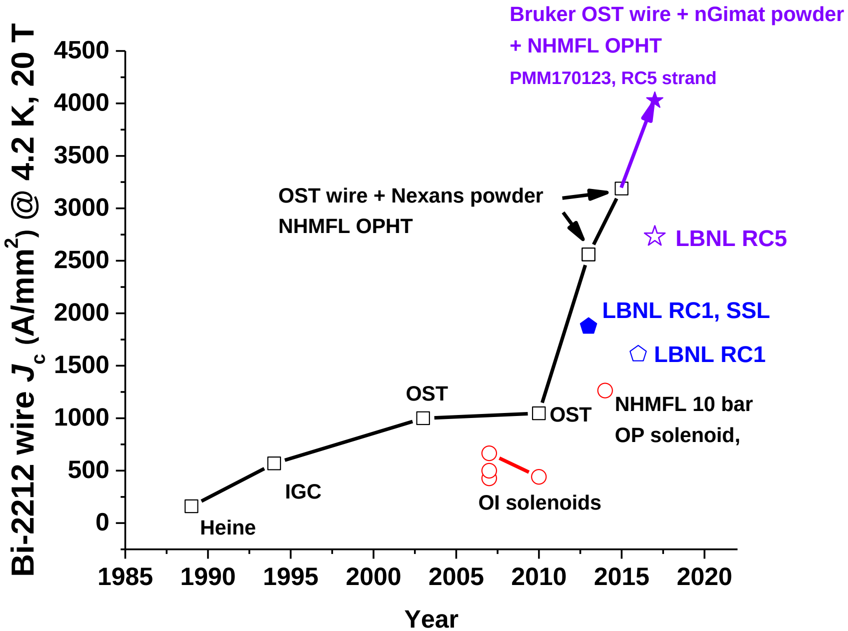
- Introduction
- Considerations for CCT insert magnets
- Bi–2212 CCT prototypes
  - BIN4 and BIN5. Fabrication status
- Design options for future prototypes
  - Using 13, 19 and 17-strand Rutherford cables
- Plans for future Bi-2212 CCT prototypes and hybrid magnet testing

Introduction
Why using Bi-2212 for inserts

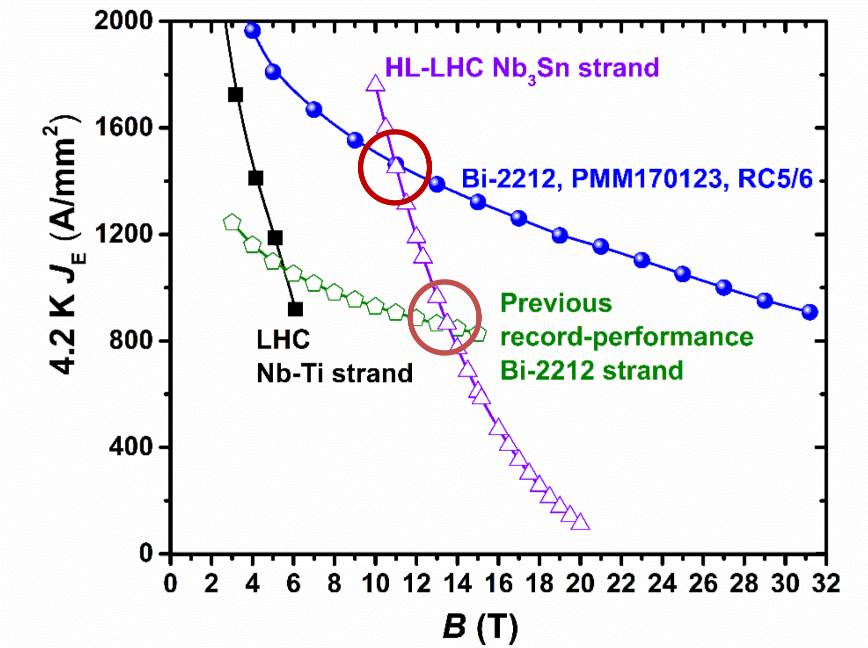
Combination of LTS and HTS technology - Example



Bi-2212 has seen significant improvement in the last years



- Improved powder
- Over-pressure heat treatment



- Now Nb_3Sn and Bi-2212 curves cross at ~11 T

Considerations for Bi-2212 CCT inserts

MDP goal for Bi-2212 inserts

- Produce 5 T as standalone
- Produce 3 T under a background field of 15 T

Strand performance

- High J_e – Strand R&D
- Over-pressure heat treatment – Furnace availability

Concerns in the axial dimension

- Length of the magnet – Heat treatment considerations
- Number of turns – Cable length
- Straight section – Field quality

Considerations for Bi-2212 CCT inserts

Concerns in the radial dimension

- Bore diameter specification (Ex. 50 mm)
- Outer diameter limitation (Ex. 120 mm)

  Challenging

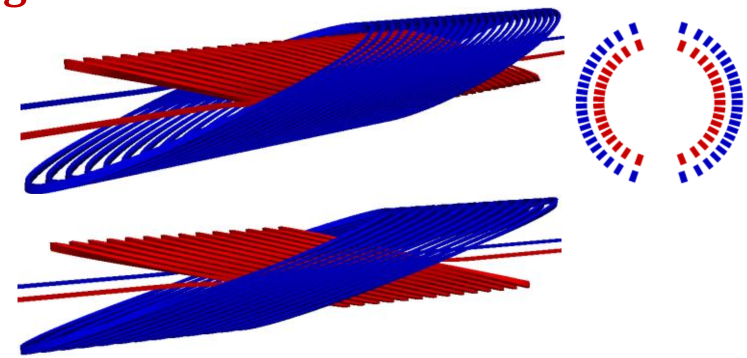
  - Mechanically coupled to the outsert (yes?/no?)
    - Spar thickness of the magnet layers
    - Al-shell thickness
  - Gap between the magnet layers and between the outer layer and the Al-shell (strongback design)
- Number of strands in the cable – Cable width

Bi–2212 CCT prototypes
BIN4 and BIN5: design and fabrication

BIN4 and BIN5 design

BIN4
Total length: **50 cm**

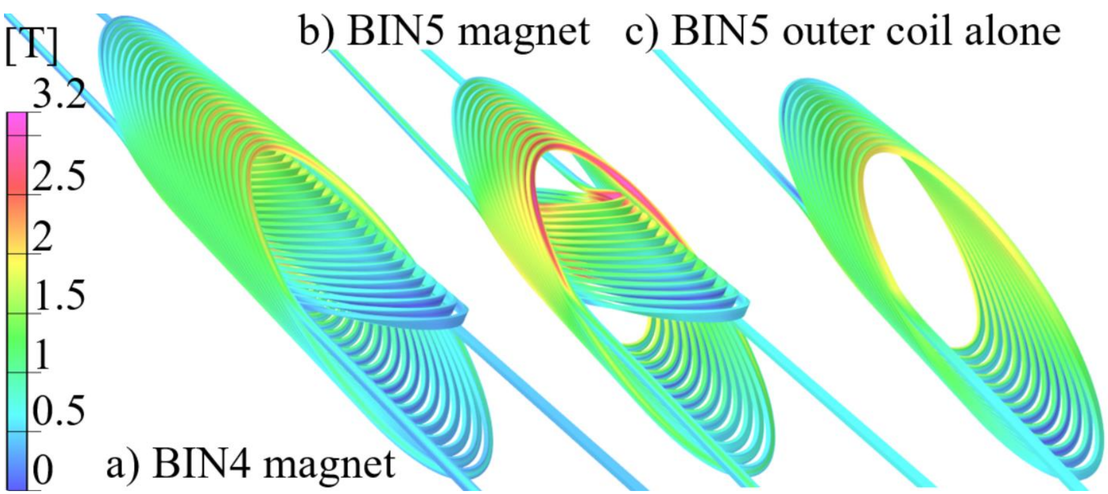
BIN5
Total length: **39 cm**

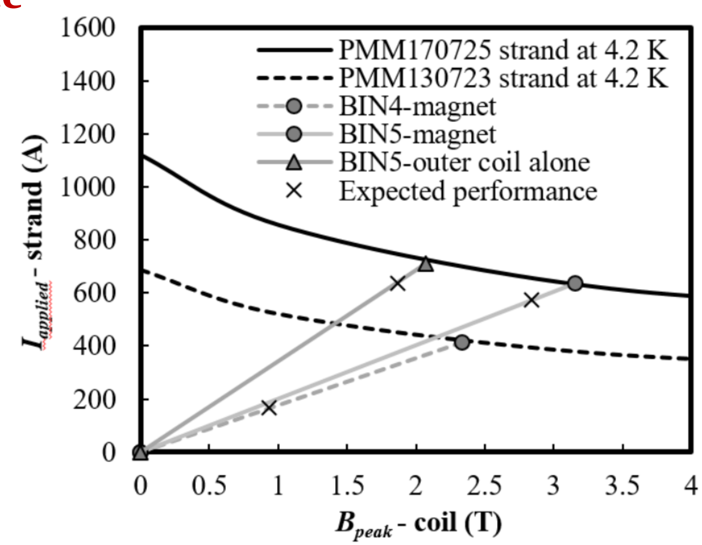


9–strand, 0.8 mm Rutherford cable

Coil parameters	Layer 1	Layer 2
Bore diameter (mm)	38.1	51.1
Spar (mm)	1.87	1.97
Outer diameter (mm)	50.3	63.5

Peak field on the conductor and expected performance





Bi–2212 CCT prototypes
BIN4: electrical shorts encountered due to insulation breakage

Winding and assembly process of BIN4

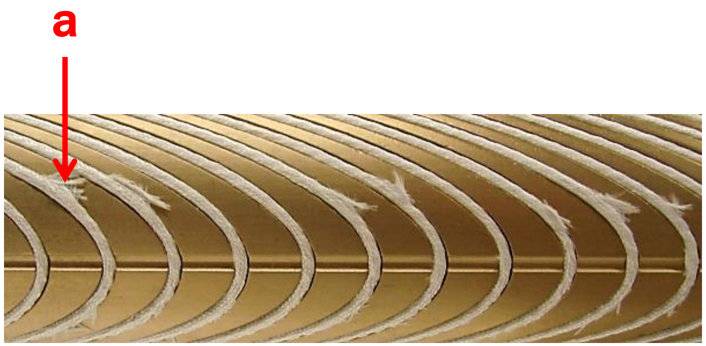
<u>Layers will be heat treated assembled</u>
(gap between layers is 0.4 mm)

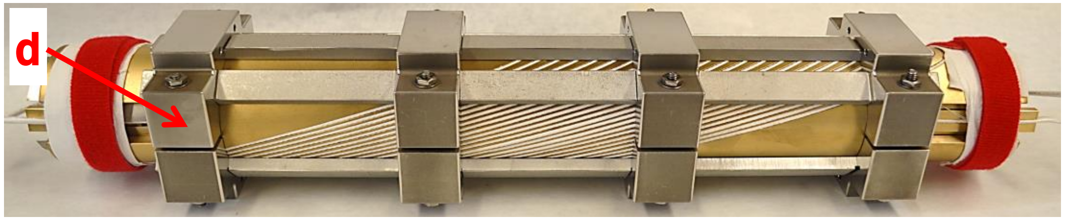
a) Insulation damage during the winding process – Need to improve the insulation.

b) Ti foil on top of the mullite cloth to ease the assembly process before HT.

c) Windows in the outer layer enable access to the splice regions of the inner layer.

d) Inconel 600 strongback before HT





Bi–2212 CCT PROTOTYPES

BIN4: lessons learned and BIN5 modifications

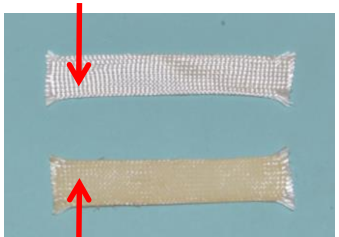
Based on the experience from the winding and assembly process of BIN4, several modifications were considered for the fabrication of BIN5:

- Paint the insulated cable with TiO_2 slurry to reduce the insulation damage during winding and eliminate the shorts between the cable and the mandrel.
- Increase the thickness of the channels at the pole region to install voltage taps and also to ease the winding process.
- Fabricate two identical outer layers of BIN5: BIN5a and BIN5b.
  - BIN5a, foreseen not to undergo a pre-oxidation cycle before the actual HT, and BIN5b, foreseen to undergo the pre-oxidation cycle (compare the conductor performance in both cases).
  - The effectiveness of the Inconel 600 strongback foreseen to be tested on BIN5b during the pre-oxidation cycle.

Bi–2212 CCT prototypes
BIN5a: new insulation approach proved to be effective for avoiding shorts

Winding and assembly process of BIN5a (no pre-oxidation cycle)

Mullite braided sleeve



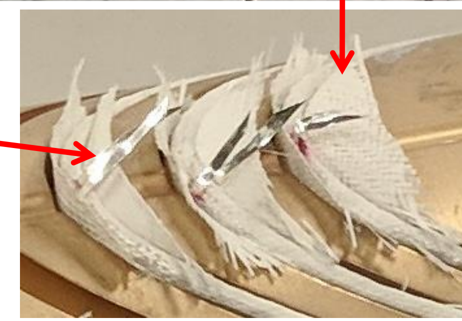
Mullite painted with TiO_2 slurry to improve the insulation

a) Silver voltage tap flags were installed at every turn.

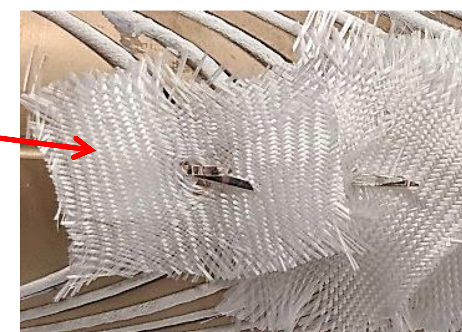
b) Extra mullite cloth painted with TiO_2 slurry placed at every pole to insulate the voltage taps.

c) Mullite cloth below every voltage tap flag to protect them during OPHT.

a



c



Bi–2212 CCT PROTOTYPES
BIN5b: strongback proved to be effective for reducing the warpage of the mandrel, but...

WINDING AND ASSEMBLY PROCESS OF BIN5B (AFTER PRE-OXIDATION CYCLE)

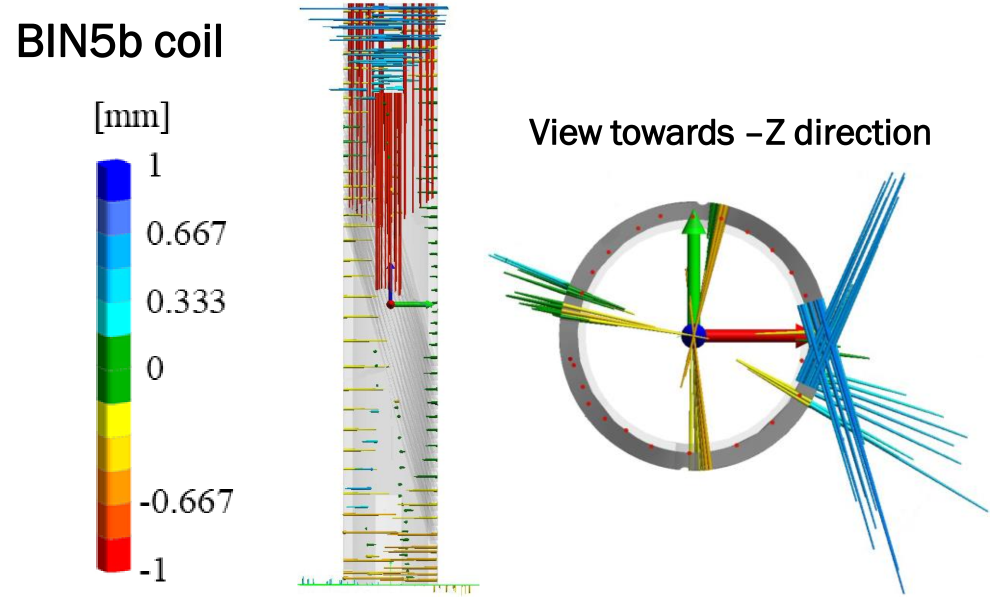
<u>The effectivenes of the strongback was tested during the pre-oxidation cycle</u>

a) BIN5 dummy after pre-oxidation HT

b) BIN5b mandrel after pre-oxidation HT (Nextel 610 cloth and Inconel 600 mesh placed between the and the mandrel).

MAXIMUM MANDREL TRANSVERSAL DISTORTION AFTER PRE-OXIDATION. MEASUREMENTS WITH FARO ARM

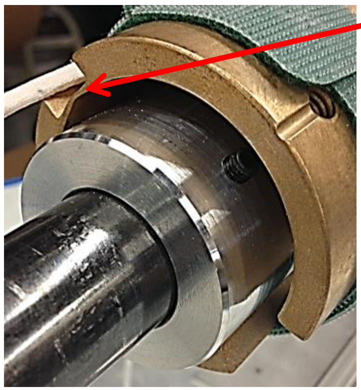
MANDREL	AFTER HT WITH STRONGBACK	AFTER HT WITHOUT STRONGBACK
BIN5 dummy	0.247 mm	0.327 mm
BIN5b	0.612 mm	Not applicable

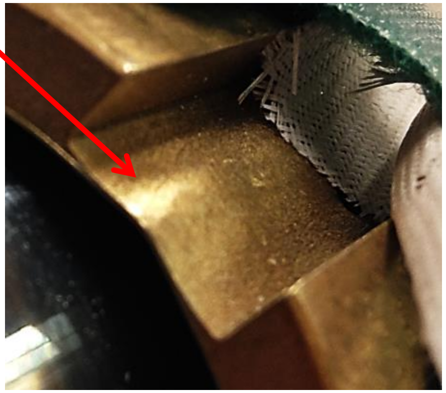


Bi–2212 CCT prototypes
BIN5b: strongback was not effective for constraining the ID of the mandrel

Winding and assembly process of BIN5b (after the pre-oxidation cycle)

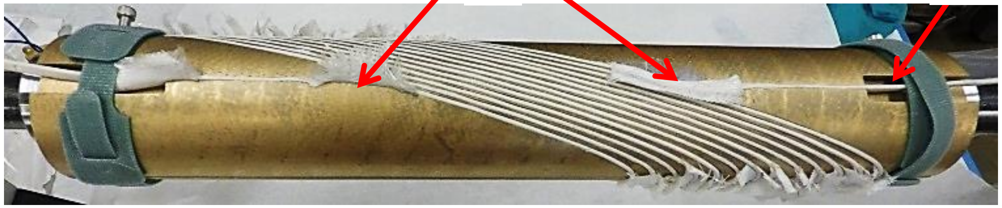
a





a) Visible bending in the splice region – a BIN5 inner layer would not fit inside this outer layer – need to constrain the ID of the mandrel during HT.

c b



b) Al-bronze boxes did not fit in the splice cavity.

c) Insulation reinforcement needed after damage caused by shrinkage of the channel in some regions.

BI–2212 CCT PROTOTYPES
Lessons learned so far

Lessons from the prototype fabrication:

- The mullite braided sleeve is not enough as insulation. Painting the cable with TiO_2 slurry avoided the shorts between the cable and the mandrel.
- The strongback decreased the mandrel warpage during HT. However if heat treating the layers separately, the gap between them should be larger enough to allow the assembly process. This will impact the OD of the magnet.
- The strongback should be re-designed such that it constrains the ID of the magnet too, and such that it can be used on coils with different OD.

Bi–2212 CCT prototypes
What we expect to learn in the short term

Status:

- BIN4 waiting to undergo 1 bar HT at LBNL – furnace needs to be calibrated.
- BIN5a and BIN5b are at FSU and will undergo OPHT.
- Successful balancing and tuning of the furnace at FSU was performed with a BIN5 dummy mandrel – dummy is ready to undergo OPHT with Rutherford cable samples

What we want to learn:

- From BIN4: HT, impregnation and test preparation processes (systematize the fabrication procedure for future prototypes).
- From BIN5a: Conductor performance after OPHT process without pre-oxidation, and mandrel distortion after OPHT without strongback.
- From BIN5b: Conductor performance after OPHT process with pre-oxidation, and mandrel distortion after OPHT with strongback.

Does the pre-oxidation cycle improve the performance of the conductor?

Design options for future prototypes

Using 13, 19 and 17-strand Rutherford cables

MAGNET DESIGN OPTIONS WITH BI-2212 RUTHERFORD CABLE, 0.8 MM DIAMETER

Targeting our high field goals

Maximum coil length: 80 cm
Tilt angle: 15 deg.

- The 13 and 19-strand designs are aggressive in terms of bore radius, insulation thickness, minimum rib thickness and gap between layers
- The 17-strand design is more realistic, it takes into account the experience from the prototype fabrication

Coil parameters	Inner layer	Outer layer	Inner layer	Outer layer	Inner layer	Outer layer
Number of strands	**13**		**19**		**17**	
Channel height (mm)	5.8		8.4		8.2	
Channel thickness (mm)	1.7		1.7		1.84	
Insulation thickness (mm)	0.1		0.1		0.2	
Bore radius (mm)	20	30.7	20	36.8	25	39.7
Spar thickness (mm)	4.5	4	8	4	4.5	2
Outer radius (mm)	30.3	**40.5**	36.4	**49.2**	37.7	**49.9**
Gap between layers (mm)	0.4		0.4		2	
Minimum rib thickness (mm)	0.25	0.32	0.25	0.33	0.30	0.38
Number of turns	61		53		48	
Straight section (mm)	236		124		112	
Cable length (m)	53.1	72.9	54.2	75.8	51.3	69.9

Mullite sleeve + TiO_2 coating

We have cable for this layer

~2 km wire (a ~10 kg billet)

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Design options for future prototypes
Keystoned cable approach to CCT magnet design

MAGNET DESIGN OPTIONS WITH BI-2212 KEYSTONED CABLE, 0.8 MM DIAMETER

Targeting our high field goals

Maximum coil length: 80 cm
Tilt angle: 15 deg.

- Adapting the previous design for using keystoned cables in both layers, increase the number of turns and the amount of conductor needed

Coil parameters	Inner layer	Outer layer	Inner layer	Outer layer	Inner layer	Outer layer
Number of strands	**13**		**19**		**17**	
Channel height (mm)	5.8		8.4		8.2	
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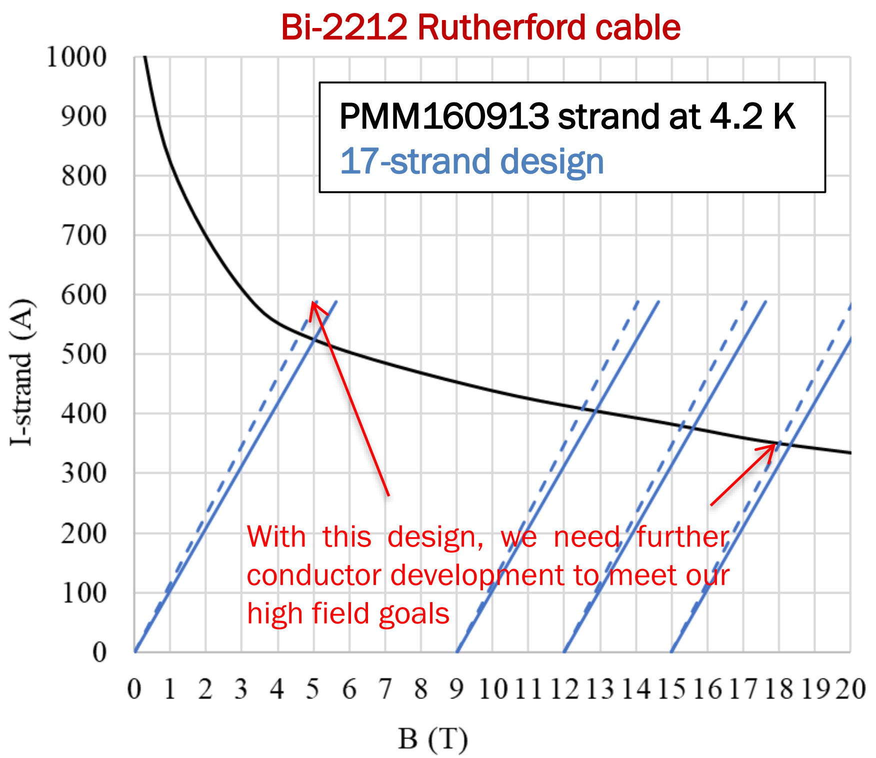
Spar thickness (mm)	4.5	4	8	4	4.5	2
Outer radius (mm)	30.3	**40.5**	36.4	**49.2**	37.7	**49.9**
Gap between layers (mm)	0.4		0.4		2	
Minimum rib thickness (mm)	0		0		0	
Number of turns	86		78		71	
Straight section (mm)	238		125		115	
Cable length (m)	74.9	102.8	79.8	111.6	75.8	103.4

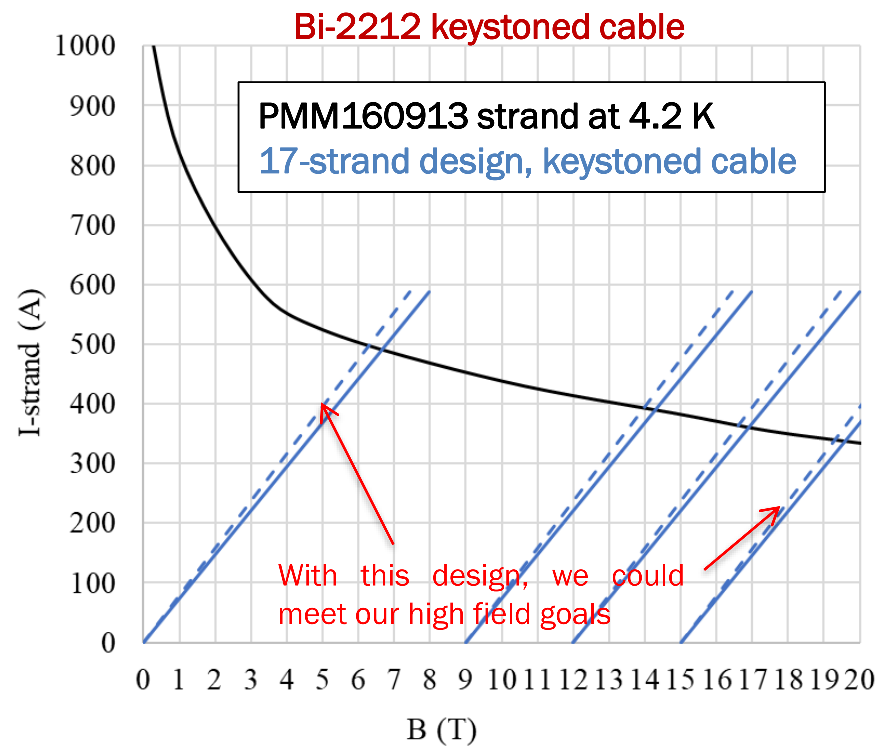
Design options for future prototypes

What we can achieve with 17-strand Rutherford cable, and how we could improve it using keystoned cable

- Solid lines represent the peak field on the conductor
- Dashed lines represent the field in the bore

- Using keystoned cables, the field increases considerably because the layers are closer to each other and the current density in the cross section of the magnet is larger





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Plans for future Bi-2212 CCT prototypes and hybrid magnet testing

2019 Q1/2	2019 Q3/4	2020 Q1/2	2020 Q3/4	2021	2022

HT RC7+RC8 test

HT BIN5_OLa and b test

New design (larger gap between layers)

BIN5_IL, and BIN5OLc and d fab & test

Design and fabricate a new strongback (able to contstrain ID, able to be used in different OD)

BIN5 standalone test

Hybrid test in CCT5

0.8 m long, 5 T 2212 CCT dipole and >15 T hybrid design

fabrication

reaction

Standalone test

hybrid test

Technology development – Mandrel, insulation, design and modeling

Al-bronze machined mandrel and/or Inconel 3D printed mandrel

BIN5-K design & fab with keystoned cable

FSU 1m OP furnace commissioned. (18-24 months)

Prototype coils

Magnet demo

Technology

Thank you!

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Conventional CCT design and keystoned cable approach