MADISON CEC/ICMC 2017

R&D on RRP Nb_3Sn wires and cables at Fermilab

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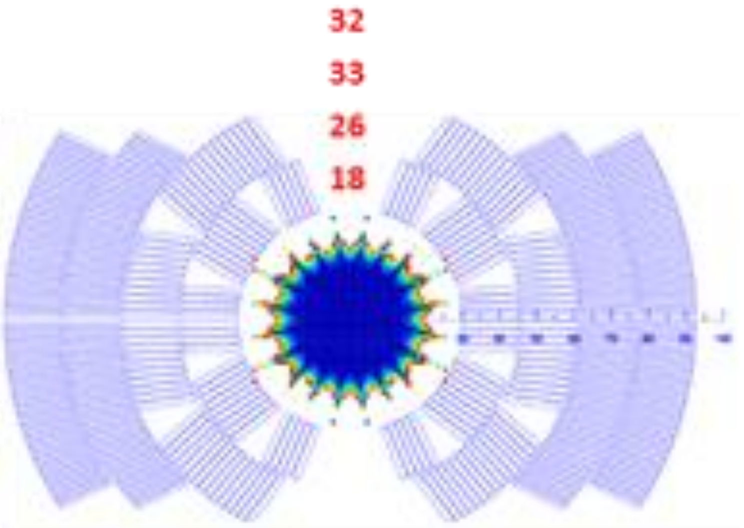
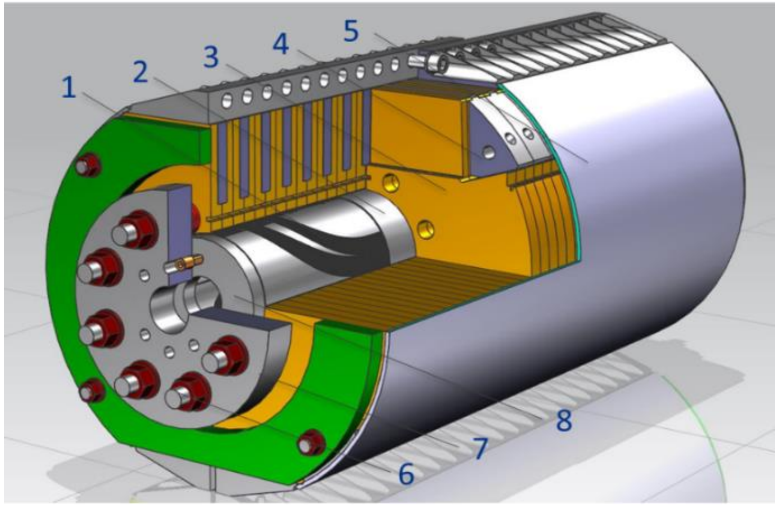
Outline

- Cable R&D for high-field dipoles
- RRP Wire Optimization with Bruker OST
- Conclusions

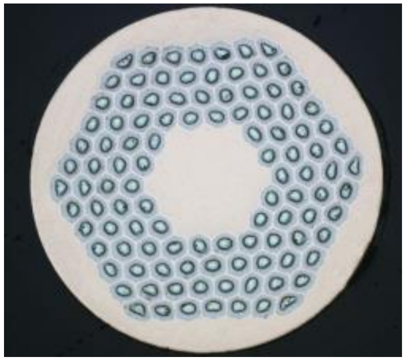
US-MDP Cos-theta 15 T Dipole

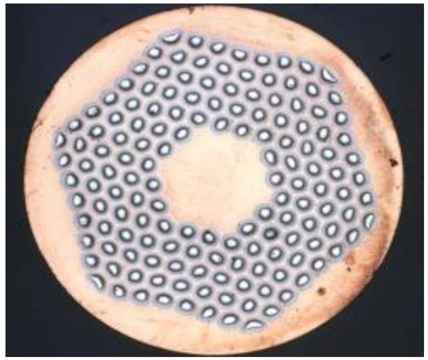
- **Coil:**
  - 60-mm aperture
  - 4-layer graded coil
  - W_{sc} = 68 kg/m/aperture
- **Mechanical structure:**
  - 2-mm StSt coil-yoke spacer
  - Vertically split iron laminations
  - Aluminum I-clamps
  - 12-mm thick StSt skin
  - thick end plates and StSt rods
  - Cold mass OD<610 mm
- **Fabrication status:** in progress
- **Planned magnet test:** Spring 2018

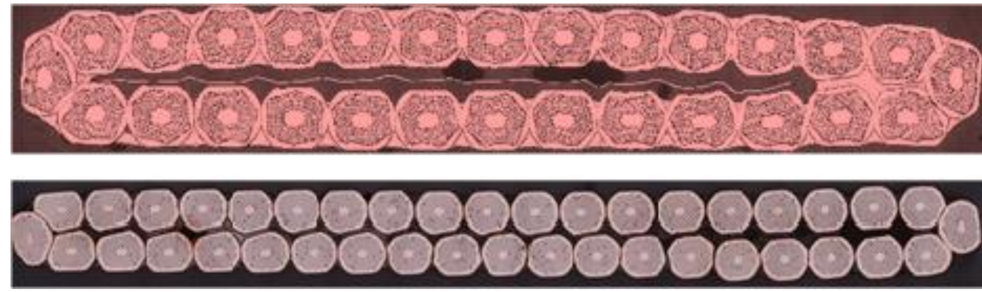




15 T Dipole: Wire and Cable Parameters







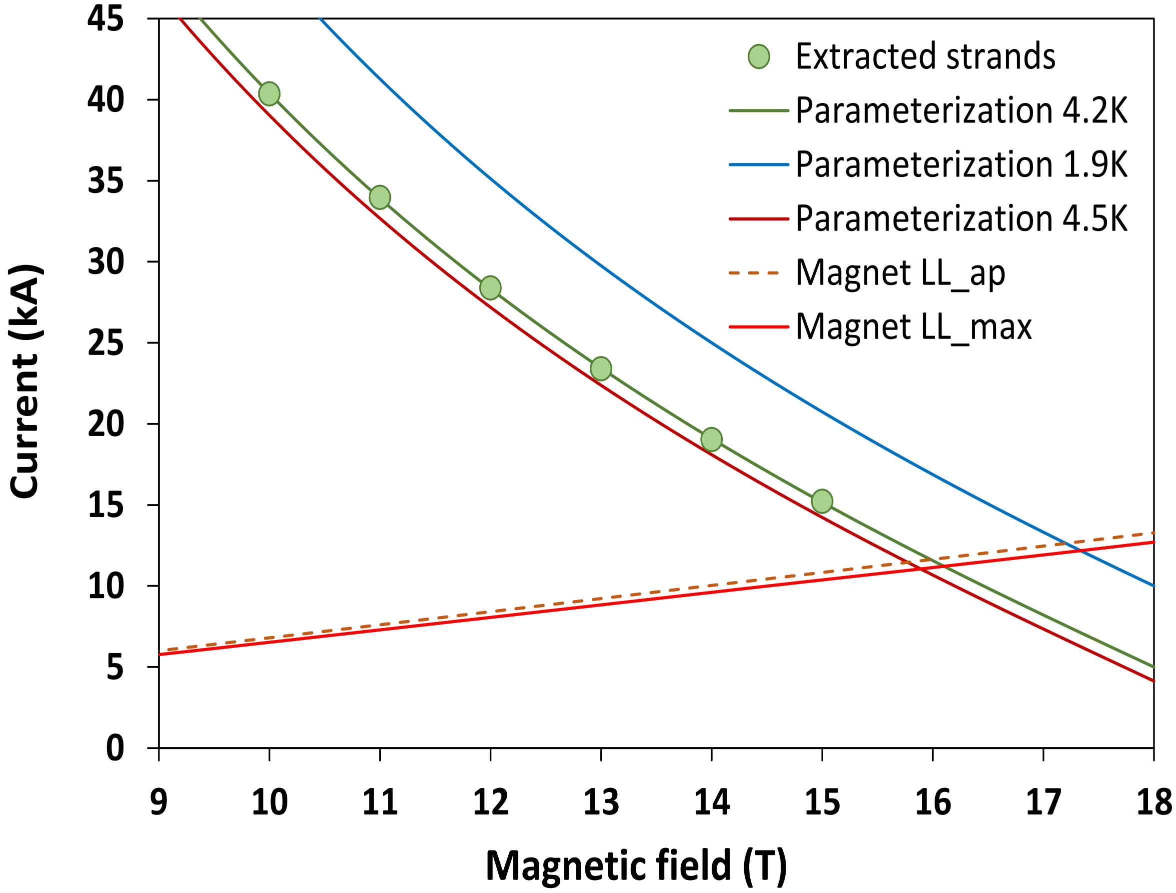
Strand ID	RRP1	RRP2
Stack design	108/127	150/169
Ternary element	Ti	Ti
Production year	2012	2014
Diameter *d*, mm	0.7	1.0
I_c (4.2K, 12 T), A	451-490	1,052-1,111
J_c (4.2K, 12 T), A/mm^2	2,560-2,722	2,597-2,710
I_c (4.2K, 15 T), A	229-245	566-619
J_c (4.2K, 15 T), A/mm^2	1,289-1,365	1,395-1,502
D_S, µm	41	58
Twist pitch, mm	14-16	23-24
Cu fraction λ, %	53.2-54.4	47.5-48.4
RRR	101-226	343-374
Final HT step	640ºC/50h	665ºC/50h

Coil	Cable N x d, mm	RRP® Strand Type	Cable length, m	Cable t_{mid} x w, mm^2	Lay angle, deg.
15 T Dipole Outer Layer	40 x 0.7	RRP1	374	1.251 x 14.71	16.8
15 T Dipole Inner Layer	28 x 1	RRP2	420	1.803 x 14.79	15.5

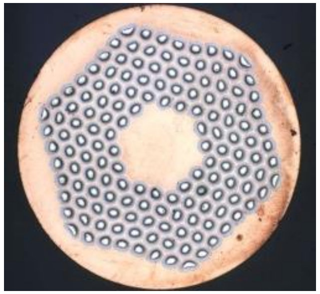
15 T Dipole: Short Sample Limit

Magnet short sample limit estimated based on extracted strand data

- Sample HT: 665°C/50 hrs (OST)
- I_{ssl}=11.05 kA (B_{ap}=15.25 T) at 4.5 K
- I_{ssl}=12.2 kA (B_{ap}=16.65 T) at 1.9 K

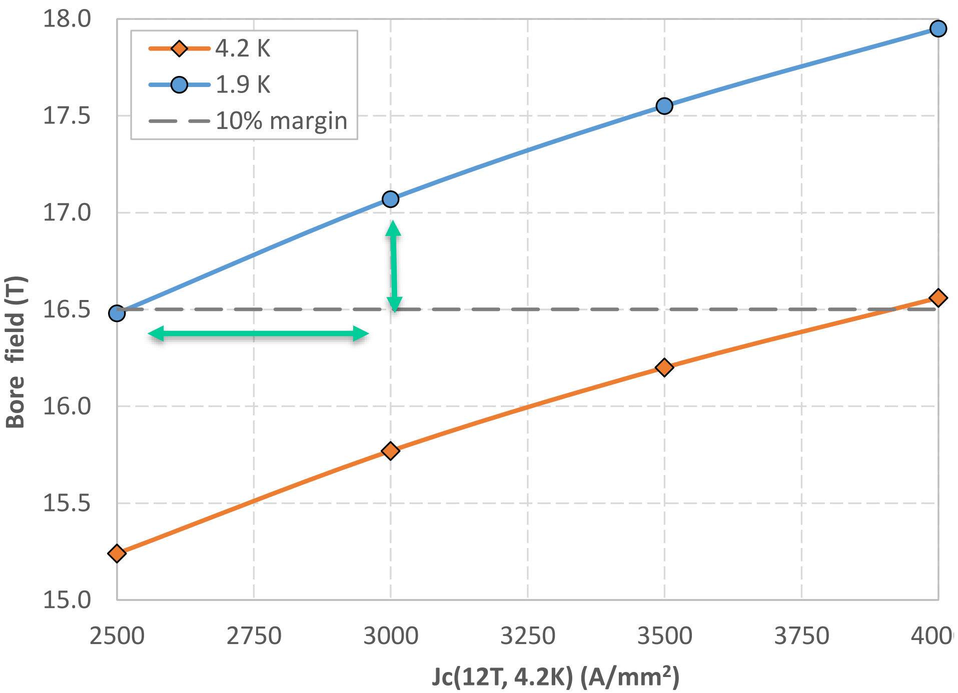


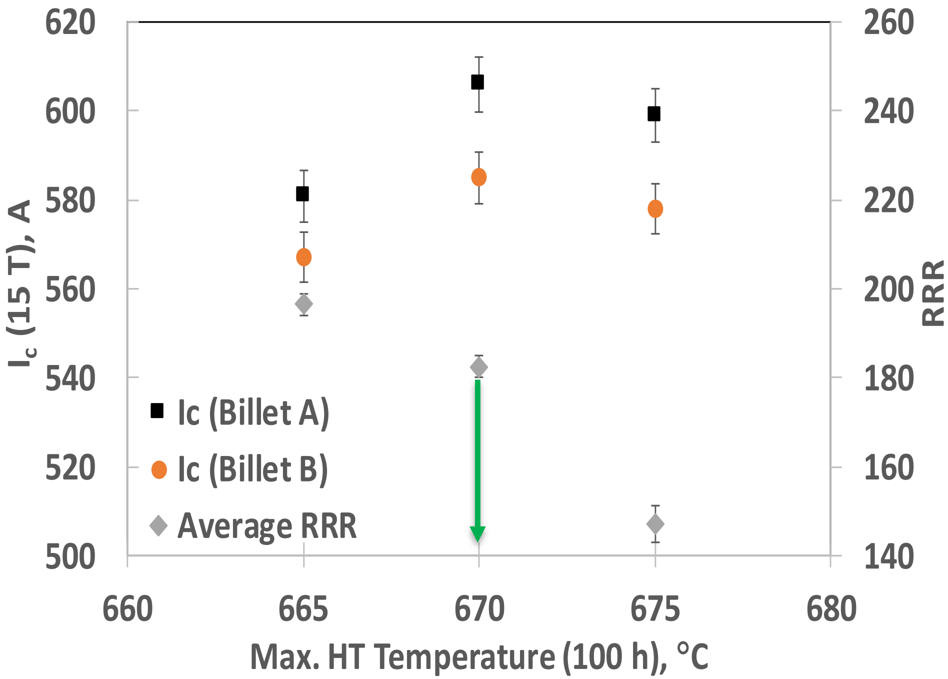
Heat Treatment Optimization for 15 T inner coil



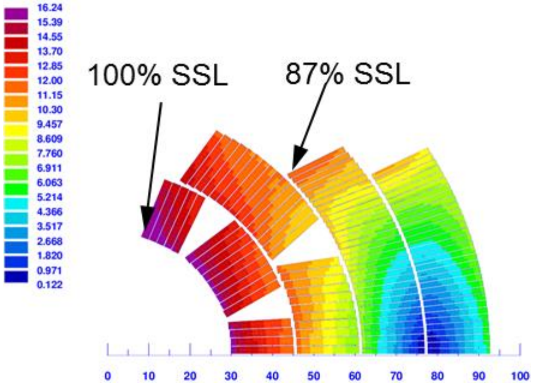
1 mm RRP150/169

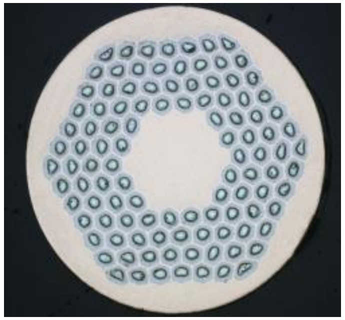
28-strand cable with SS core



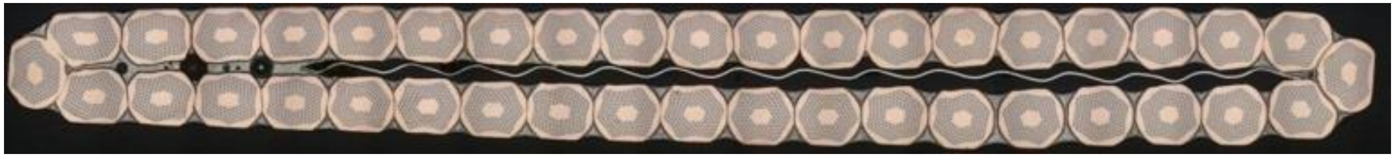


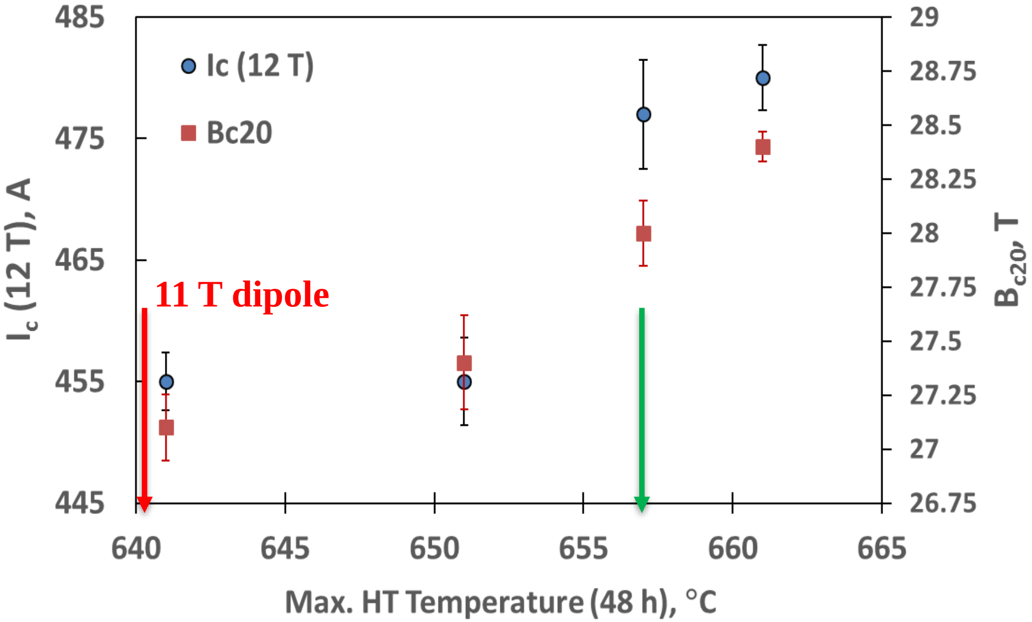
Heat Treatment Optimization for 15 T outer coil

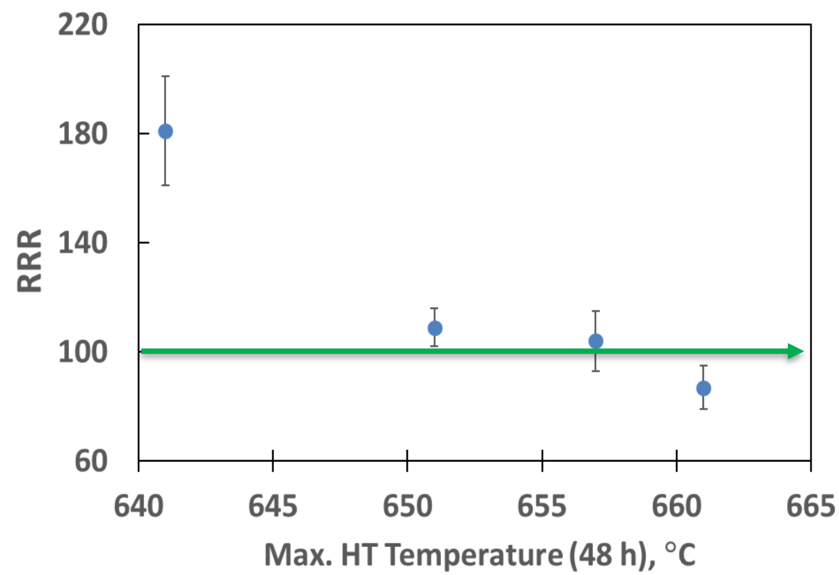




0.7 mm RRP108/127
40-strand cable with SS core

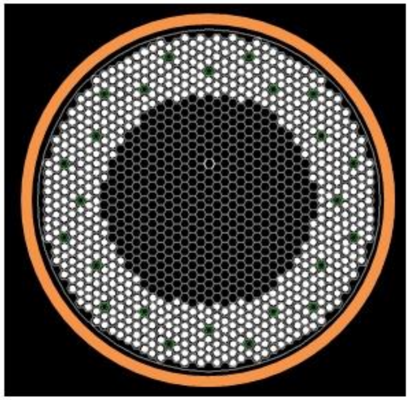


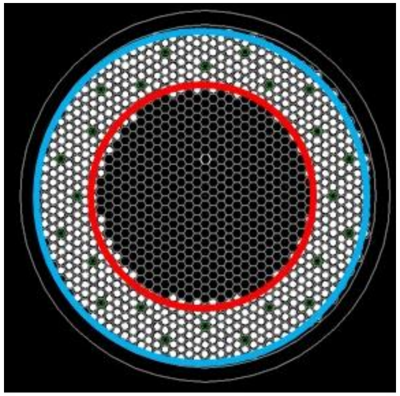




RRP Strand Optimization with Bruker OST

- **Goal: increase J_c(15T) with an ultimate target of 2 kA/mm^2 for a 169 stack strand at 1.0 mm (D_s~58 μm) by modifications to sub-element.**
- **The following 3 billets with standard Nb:Sn=3.4:1 (highest J_c) and 150/169 Ti doped sub-element were produced:**
  - **Nb7.5wt%Ta diffusion barrier, standard monofilament LAR ~0.20**
  - **Monofilament LAR increased from the standard ~0.20 to ~0.23**
  - **Graded monofilament LAR – innermost row LAR ~ 0.25, all middle rows LAR ~ 0.20, outermost row LAR ~0.14**
- **All billets, as well as 0.8 to 1.2 mm wire samples, were delivered end of July 2016.**



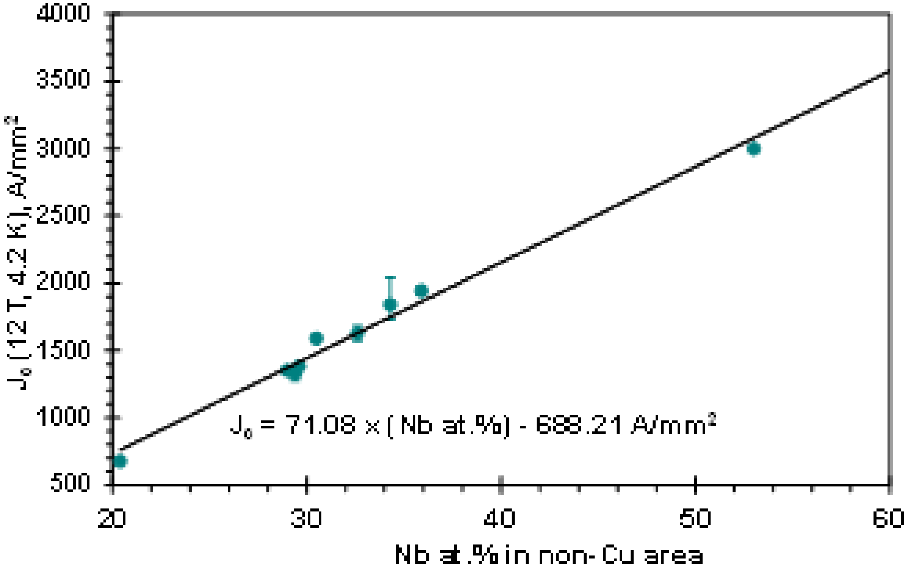


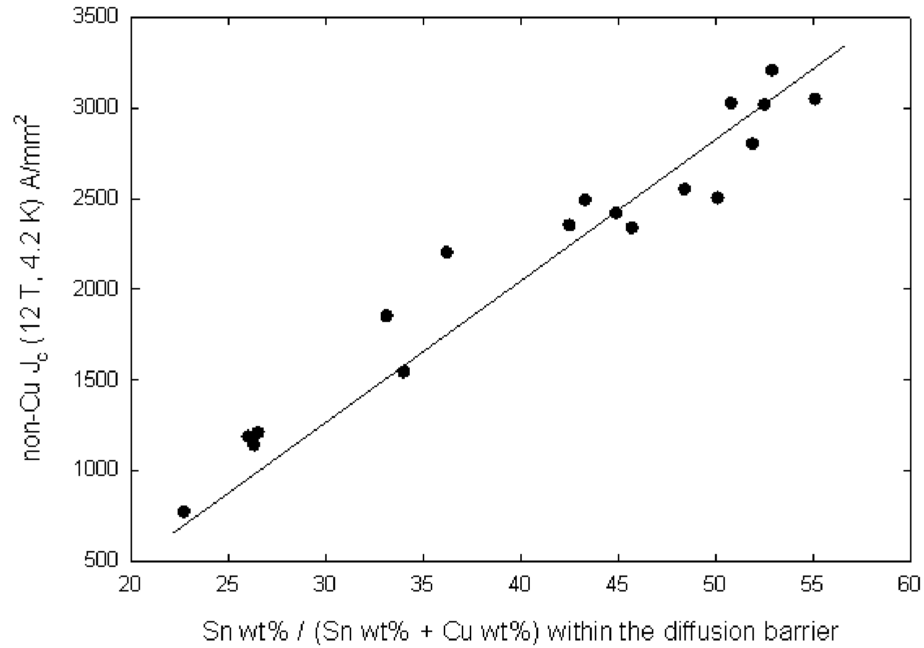
0.8-1.2 mm RRP150/169 wire results

Strand ID	RD1	RD2	RD3
Stack design	150/169	150/169	150/169
Ternary element	Ti	Ti	Ti
Production year	2016	2016	2016
Diameter *d*, mm	0.8 to 1.2	0.8 to 1.2	0.8 to 1.2
I_c (4.2K, 15 T) for 1 mm, A	651 max.	657 max.	665 max.
J_c (4.2K, 15 T) for 1 mm, A/mm^2	1,713 max.	1,684 max.	1,715 max.
D_S, µm	46 to 69	46 to 69	46 to 69
Cu fraction λ, %	50.9-51.6	49.9-50.5	50.5-50.8
B_{c2}(4K) at J_c^{max}, T	26.7	27.0	26.5
RRR at J_c^{max}	161	30	97
Final HT step	680ºC/50h	680ºC/50h	665ºC/100h

- **No major J_c difference was seen with respect to the standard high-J_c sub-element design**
  - **RRR problem caused by bad barrier in one billet.**
- **Deformed wires from these billets did not behave better than reference deformed wires.**
- **This level of J_c was achieved at 53 at.%Nb that is the limit with the available real estate in the wire.**
- **To go beyond the present state-of-the-art performance the inherent flux pinning increase is needed.**

State of the Art





As well-known, the J_c of internal tin strands is proportional to the Nb content that can be packed in the wire. To achieve a J_c(4.2K, 12T~ 3,000 A/mm^2 a 53% Nb at.% is required, which is the limit with the available real estate in the wire. It is therefore unlikely to go beyond the present state-of-the-art performance without acting on the inherent flux pinning mechanisms of Nb_3Sn.

E. Barzi, A.V. Zlobin, "Research and Development of Nb3Sn Wires and Cables for High-Field Accelerator Magnets," IEEE Trans. on Nuclear Science, vol. 63 (2), April 2016, pp. 783-803.

Conclusions

- **For the 15 T Dipole demonstrator, cables were designed and optimized based on the properties of RRP Nb_3Sn wires**
- **Sensitivity studies to heat treatment were performed to push performance to nominal required**
- **Next: 10-stack studies for mechanical properties**
- **Breakthroughs in J_c for Nb_3Sn wire is not possible without acting on its inherent flux pinning mechanisms**
- **See also "Innovative Nb_3Sn Thin Film Approaches and their Potential for Research and Applications", this conference**