LUVATA View on the Dream Nb_3Sn Conductor for FCC

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FCC Week, Washington, DC
March 2015

Partnerships beyond metals

Key Projects with Luvata Participation:

- NbTi for Fermi Lab (>90%), CERN-LHC (30%), GSI-SIS100
- Nb_3Sn for Fusion Programs
  - ITER Central Solenoid Model Coil (CSMC): 1991~1995
  - KSTAR Advanced Performance Strand (HP-3): 1997~2006
  - US & EFDA ITER-TF Prototype Strands: 2004~2007
  - US ITER-TF: 2009~2012
- High Jc Nb_3Sn Conductor Development for HEP
  - US CDP: 2001~2003
  - Next European Dipole (NED): 2007~2010
  - CERN Nb_3SN R&D for LHC Upgrades: 2014~Present

Mass Production Started 1996 with KSTAR:

- First fusion machine utilizing all Nb_3Sn for TF coils in mass production strand quantity.
  - 50% of Nb_3Sn: Produced 12 t of HP-3 type Cr-plated wire
  - 100% of NbTi: Produced 12 t for PF
  - Increased Nb_3Sn billet size to 60 kg, unit length > 13 km
  - Manufacturing equipment upgrade enabling mass production
  - Production rate achieved 1.8 t per month

- Enhanced Performance
  - Non-Cu J_c: 850-900 A/mm^2 (4.2 K, 12 T)
  - Non-Cu Q_h: 220-270 kJ/m^3 (±3T cycle)

Equipment Upgrade for Larger Billet Unit

2.2 m - BB

1.5 m - BB

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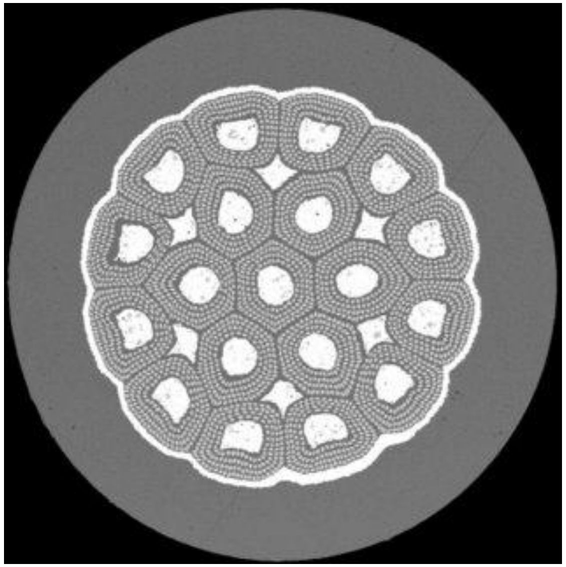
Nb_3Sn Production for US ITER-TF



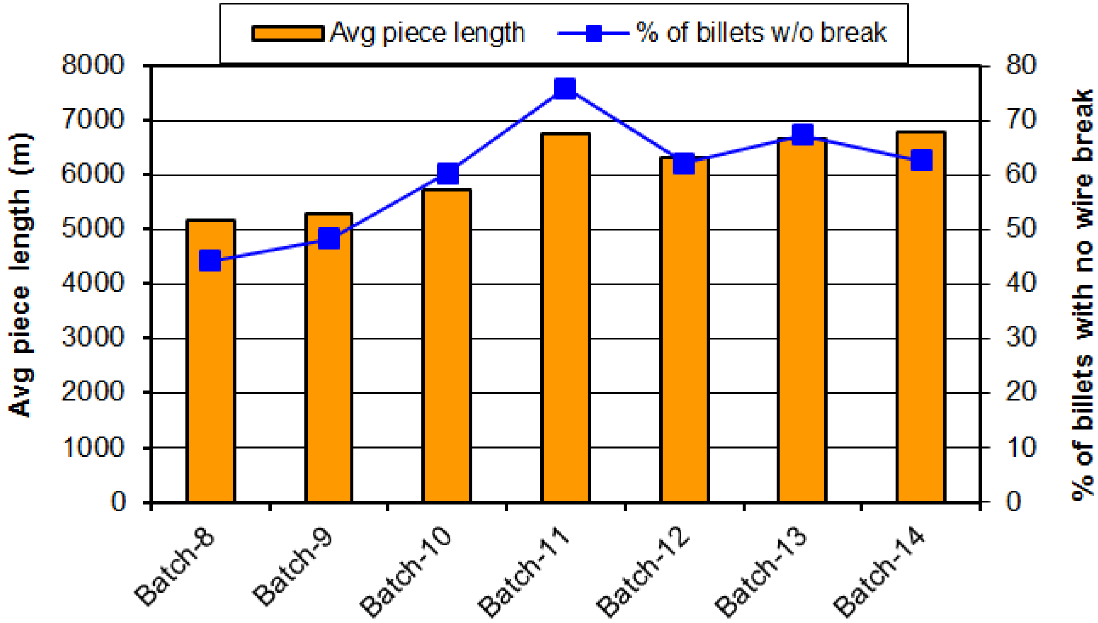
Cr-plated TF SC Strand:

- 32 t of Cr-plated Nb_3Sn (6430 km)
- 2.3 t / mo. x 14 monthly batches

Cr-plated TF Cu Strand:

- 23 t of Cr-plated Cu (4795 km)
- 1.6 t / mo. x 14 monthly batches

Piece Length Performance - ITER TF Strand

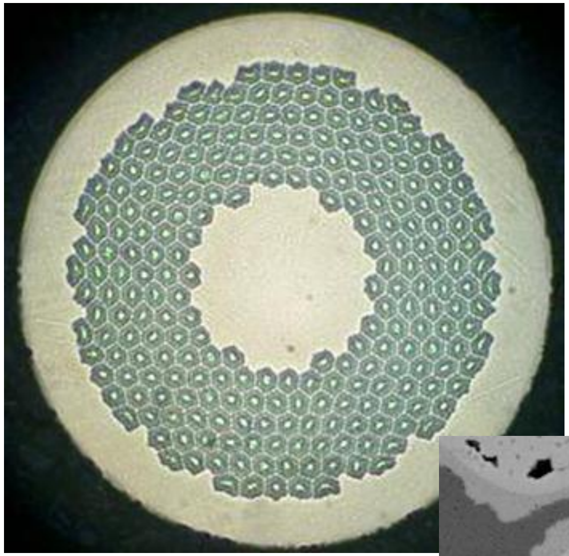


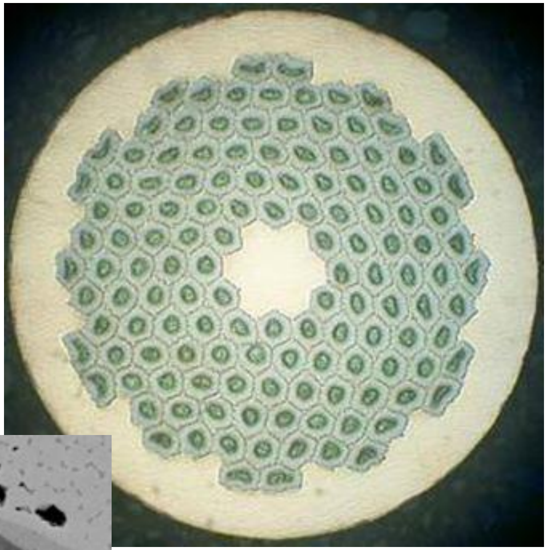
- Average piece length:
  - Over ***6600 m (mature process)***
- Billets with no wire breaks:
  - ***2/3 of billets in single length***

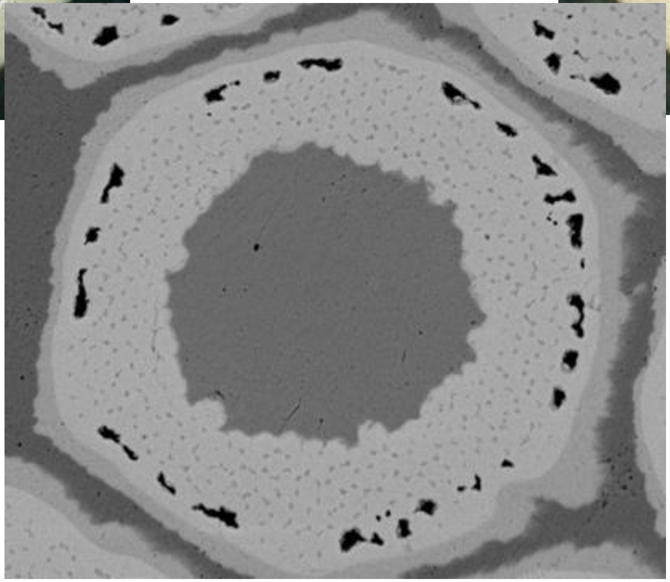
High Jc Nb_3Sn for HEP:

- Nb Rod-in-Cu Tube (RIT) Process
  - Ti addition through Sn core
- R&D for CERN
  - Wire for HL-LHC upgrades
  - Wire design for: Jc, D_{eff}, RRR & **drawability**
  - Restacking architecture
  - SnTi microstructure refinement

RIT-3: *NED*







Design: B1

- 1.25 mm
- **258/313** pattern
- Cu: 55%
- Subelement: 45 μm

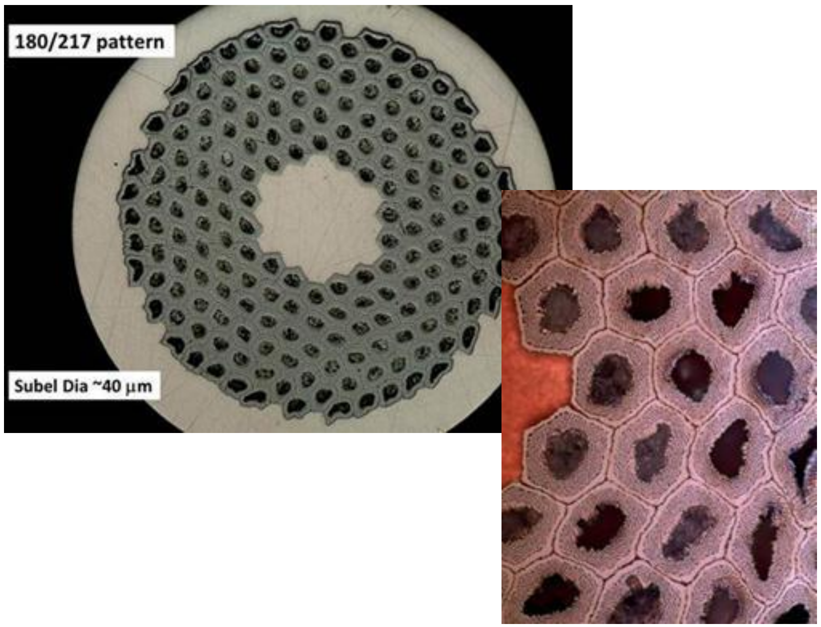
Design: B2

- 1.25 mm
- **132/139** pattern
- Cu: 54%
- Subelement: 78 μm

RIT-4: *CERN R&D – 1st set*

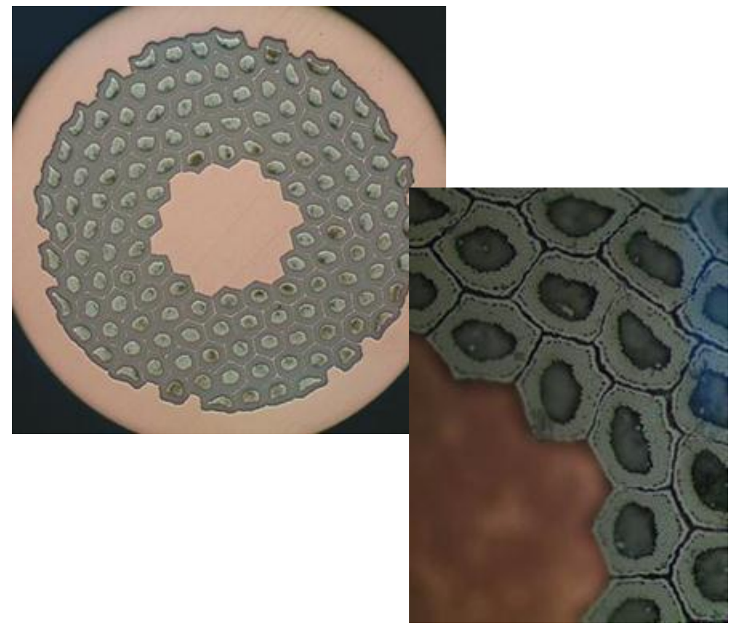
Rod-In-Tube (RIT) – Increased filament count, thicker Nb barrier and SnTi core with improved microstructure.

180/217 Stack



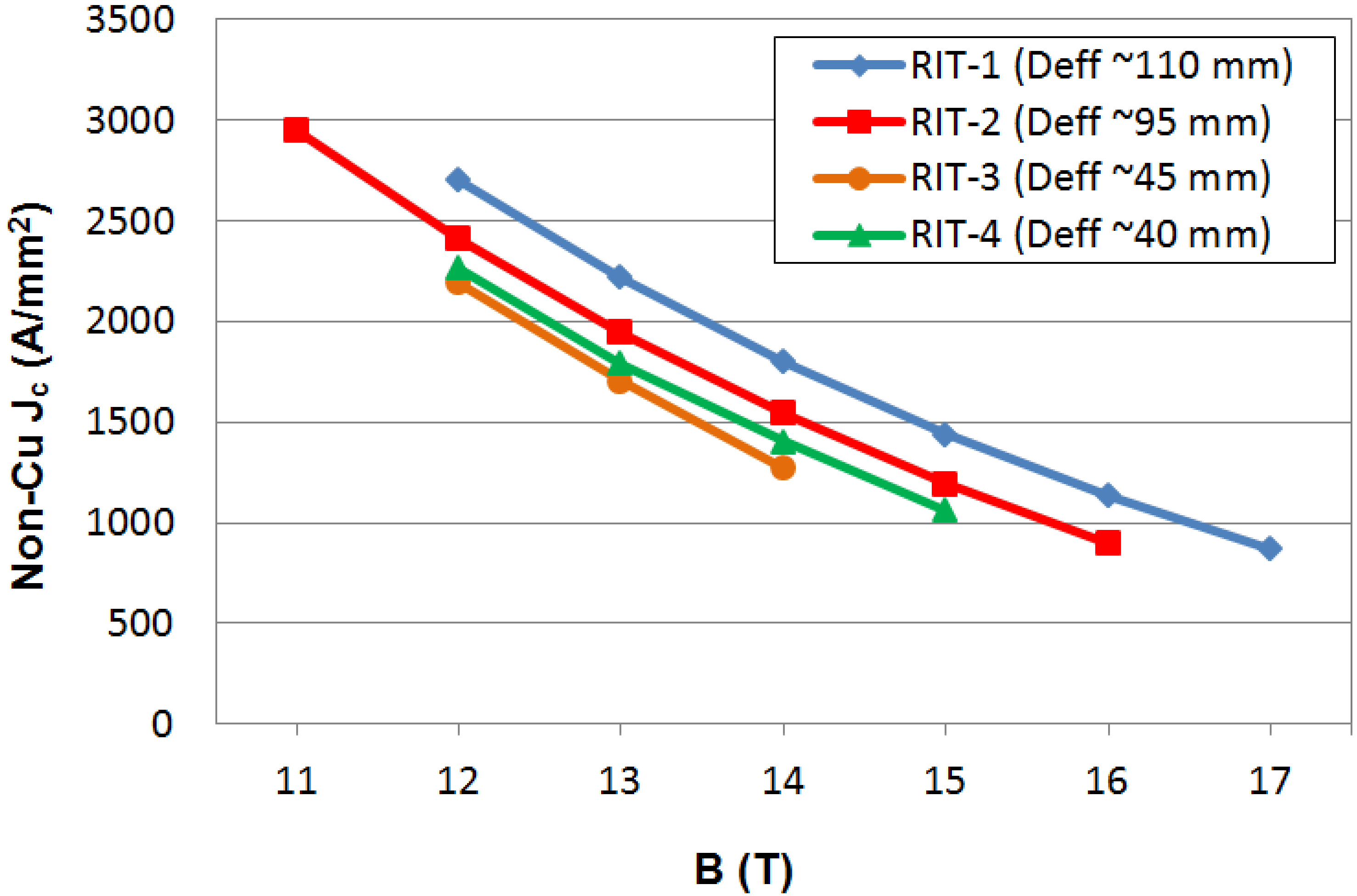
80% of wire > 400 m
Subelement dia ~40 μm

132/169 Stack



82% of wire > 400 m
Subelement dia ~45 μm

Non-Cu Jc vs. B:



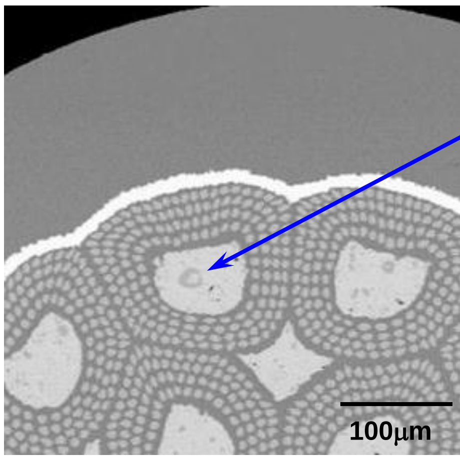
RIT-1 (Deff ~110 mm)
RIT-2 (Deff ~95 mm)
RIT-3 (Deff ~45 mm)
RIT-4 (Deff ~40 mm)
Non-Cu Jc (A/mm2)
3500
3000
2500
2000
1500
1000
500
0
11
12
13
14
15
16
17
B (T)

Effect of Ti_6Sn_5 Precipitate Size:

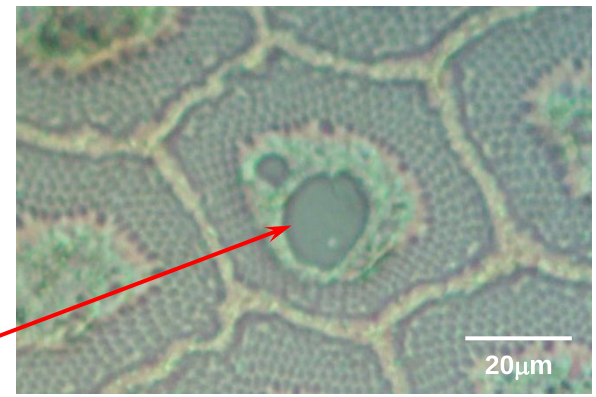
SnTi core approach required further refinement of microstructure and uniformity of precipitate for reduced subelement size.

D_{subel} > 110 mm

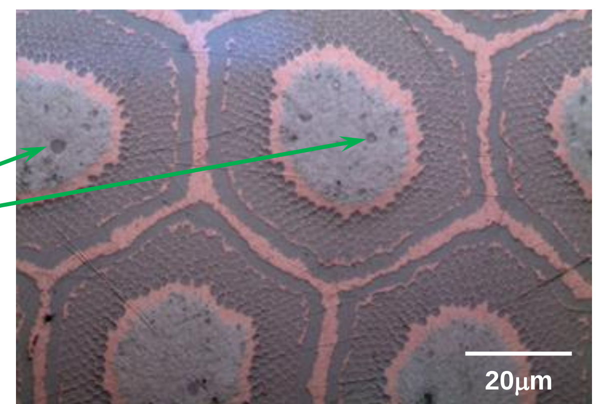
D_{subel} < 50 mm



Particles much smaller than tin core size



Larger particles becomes problematic!!



Refined microstructure

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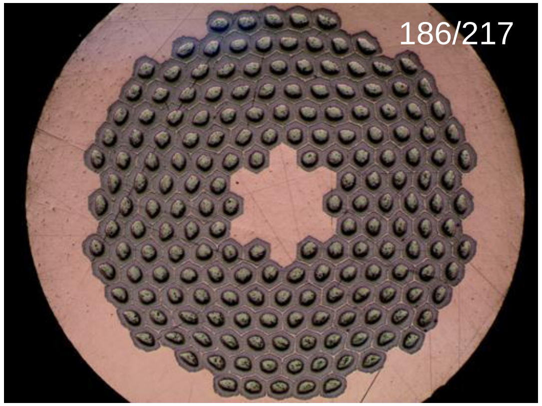
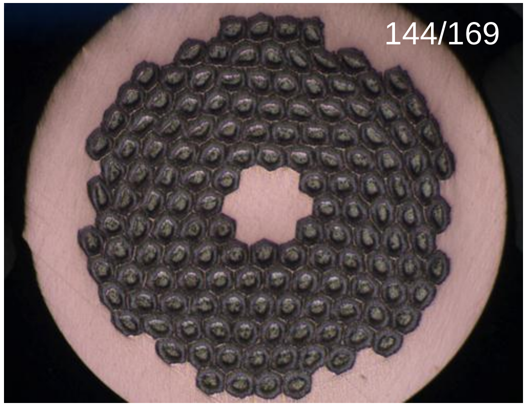
RIT-4 (modified): *CERN R&D (2nd Set)*

- Some issues on the first set of restacks:
  - Some subelements distortion is considered a primary factor to low Jc and RRR.
- Modified Restacking Architecture:
  - A specially profiled copper tube along with conforming subelement shape to produce more uniform subelement shape and size.



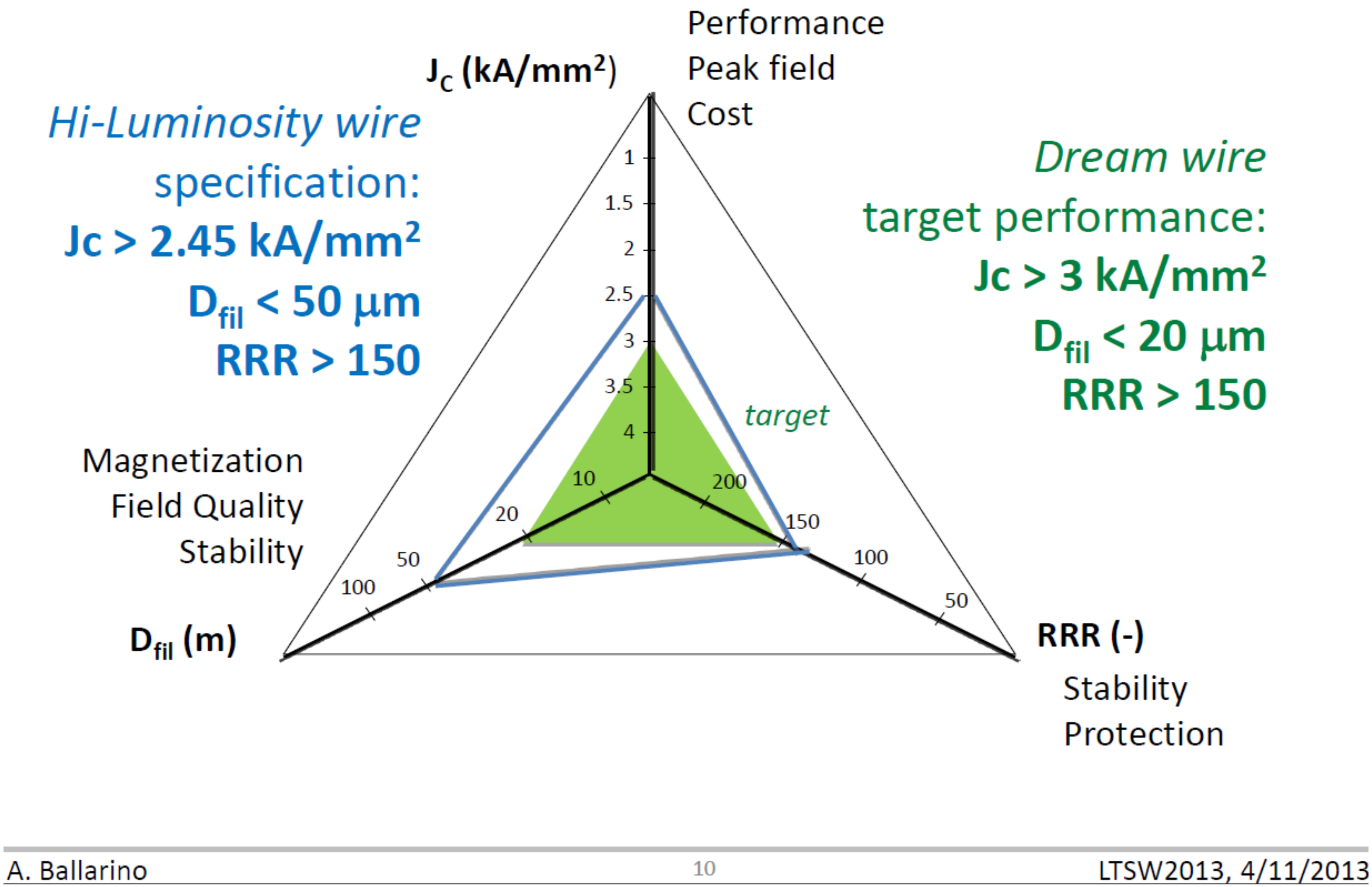


In the process of evaluating the performance.

Nb_3Sn Performance Targets:

			Hi-Lumi	FCC
Starnd Diameter	mm		0.7~0.85	0.7~1.0
Non-Cu Jc	A/mm^2	12 T	≥ 2450	≥ 3400
		15 T	≥ 1350	≥ 1850
		16 T	-	≥ 1500
$\mu_0 \Delta M$	mT		-	≤ 150
$\sigma(\mu_0 \Delta M)$	%		-	≤ 4.5
D_{fil}	μm		≤ 50	≤ 20
RRR	-		≥ 150	≥ 150
Unit Length	km		≥ 0.4	≥ 5
Cost (16 T, 4.2 K)	$/kA-m		-	≤ 5

Nb_3Sn Specifications:



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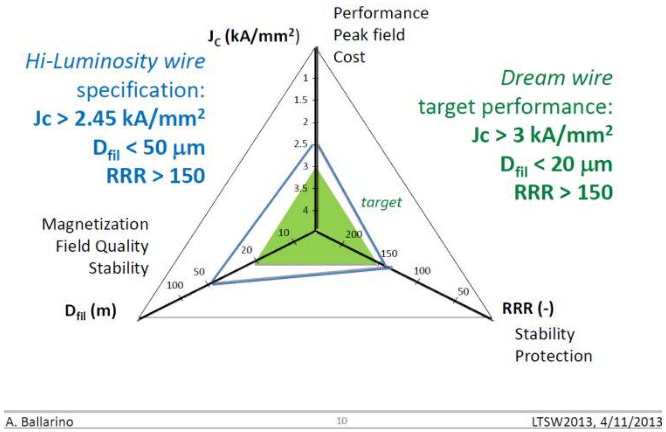
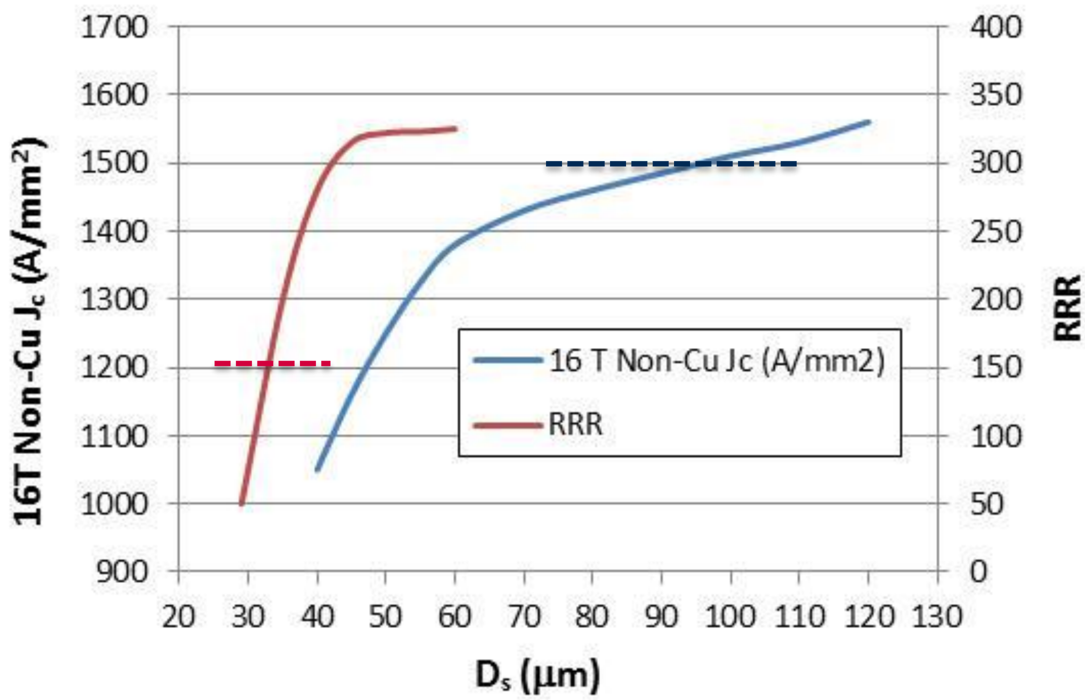
4^{th} & 5^{th} dimensions



- Long piece lengths >5 km
- Reasonable cost <$5 /kAm at 16T

All these 5 dimensions are inter-related and counter-acting

Subelement Size Effect: *Typical Trend*



Both J_c and RRR dropping rapidly below 40~50 μm.

Extrinsic factors are responsible

Basic Demands:

- Jc: Finer grain A15
  - Dopants to Nb (Zr, Hf etc) - Layer Jc
  - Minimize SE distortion
  - Optimized HT
- RRR: Reliable barrier
  - Sufficient barrier thickness
  - Uniform deformation
  - Optimized HT
- Ds / Deff: Composite Ductility
  - Compatible materials
  - Low degradation in cabling
  - “Smart” wire architectures

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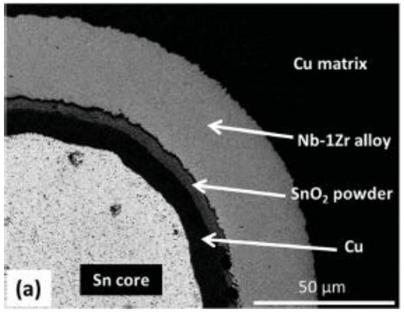
Basic Demands:

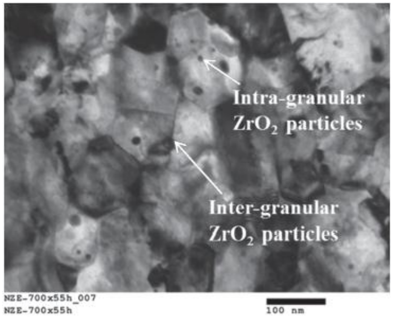
- Long Piece Lengths
  - Large restack assemblies (100 to 150 kg billet size)
  - Freedom from internal defects!
  - “Clean Room” factory environment

- Affordable Cost: Process driven
  - Large restack assemblies (100 to 150 kg billet size)

Potential for J_c Enhancement:

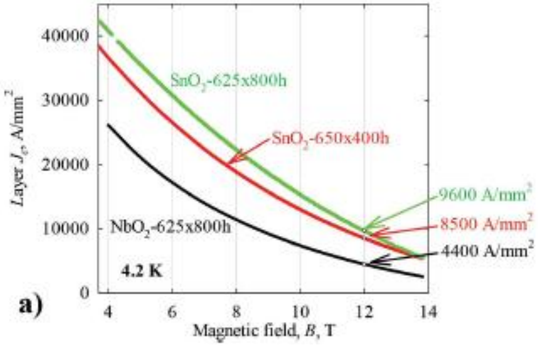
- Nb_3Sn grain refinement through internal oxidation.
  - NbZr alloy with oxygen supplied via oxide powder.

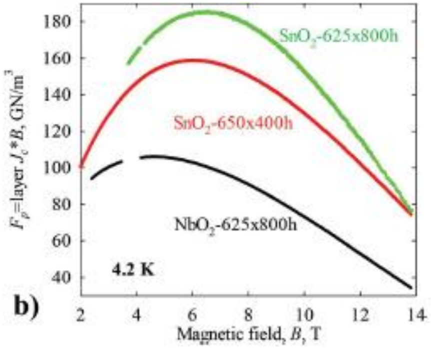




Substantial increase in J_c further is – ***fundamentally feasible!!***

  - **Layer J_c measured nearly 10,000 A/mm² at 12 T, 4.2 K**.

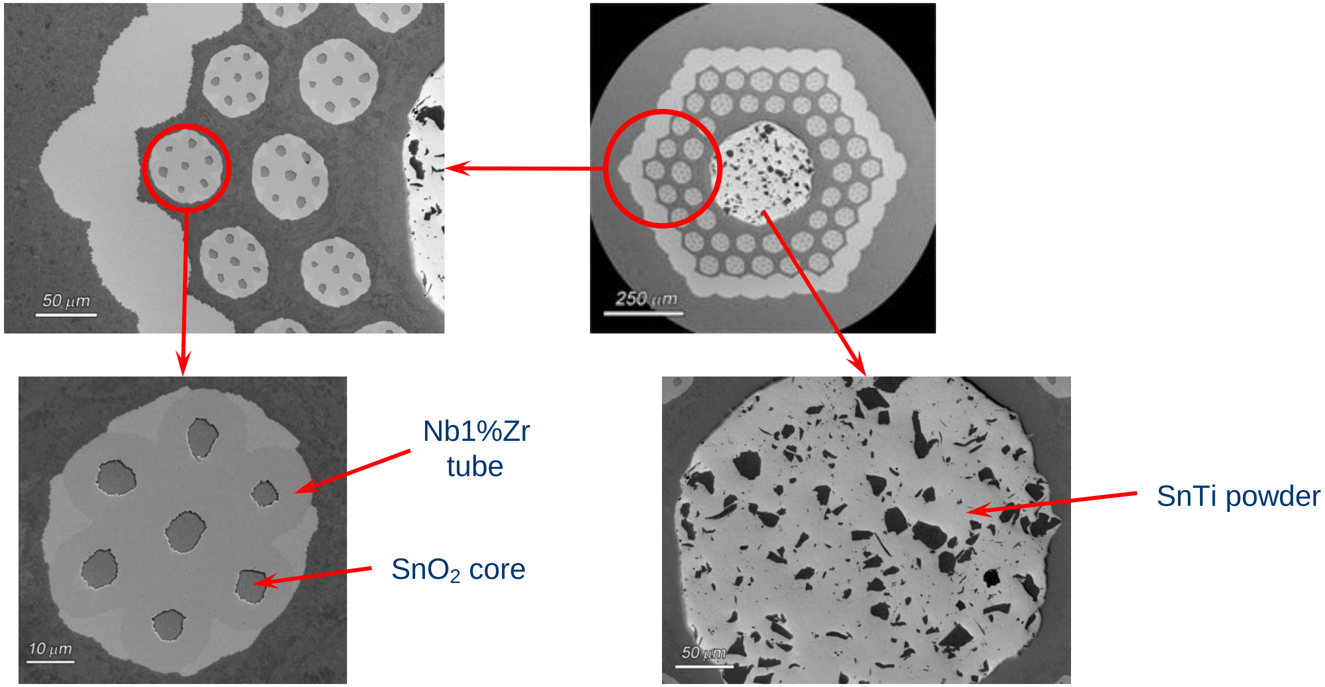




X. Xu and M. Sumption, et at. – Adv. Mater. 2015, 27, 1346-1350

Potential for Finer D_s:

- A wire layout for improved fabricability.
  - Oxygen introduced from SnO_2 core to Nb1%Zr tube.
  - Stacking architecture (hexagon or octagon) to promote uniform co-reduction.



L. Motowidlo – Supramagnetics
SBIR Phase-2, 2015

Final Thoughts

- It is unlikely that current distributed barrier Internal-Tin or Tubular approaches will overcome the hurdles
- New and "out-of-the-box" thinking is necessary in the selection of material combination and wire architectures
  - Control of "Extrinsic Factors" is key
  - Questions need to raised early if an approach is scalable
- Scale-up of final stage assembly
  - Difficulties/challenges grossly ignored in the past
  - Several years of production practice to understand "economics"
- Proper effort and adequate funding are essential
  - 10% of estimated SC budget for R&D! Will pay back multi-fold

Anyone can make a sample with exciting properties;
Can you make 5 km with the same performance in every mm and in tonnage quantity?
-Bruce Strauss

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Thank you !

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Partnerships beyond metals