OXFORD INSTRUMENTS

The Business of Science®

Nb_3Sn Conductor Technology for the FCC

M.B. Field, H. Miao, M. Gerace, and J.A. Parrell

Oxford Superconducting Technology, Carteret, NJ 07008 USA

Opportunities for Nb_3Sn Development

The Business of Science®

Acknowledgements

- U.S. DOE - High Energy Physics (CDP work through LBNL)
- Lawrence Berkeley National Laboratory
- Fermi National Accelerator Laboratory
- Brookhaven National Laboratory
- European Organization for Nuclear Research (CERN)
- ASC - Florida State University / NHMFL

- Thank you for your continued support

Introduction – Nb_3Sn for FCC

Property	Units	Values
Strand diameter	(mm)	0.5 mm to 1.0 mm
J_c(4.2 K, 16 T)	(A/mm^2)	≥ 1500
μ_oM(1 T, 4.2 K)	(mT)	≤ 150
σ(μ_oM)(1 T, 4.2 K)	(%)	≤ 4.5
D_{eff}	(μm)	≤ 20
RRR		≥ 150
Unit Length	(km)	≥ 5 km

"Targets for R&D on Nb_3Sn conductor for High Energy Physics", Ballarino and Bottura

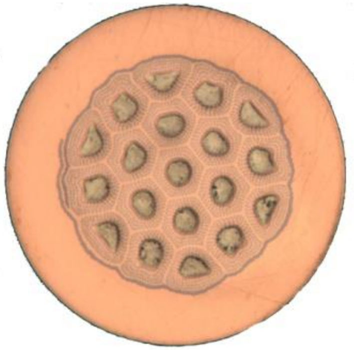
Property	Units	Values
Strand diameter	(mm)	0.5 mm to 1.0 mm
J_c(4.2 K, 16 T)	(A/mm^2)	$\geq$ 1500
$\mu_o M$(1 T, 4.2 K)	(mT)	$\leq$ 150
$\sigma(\mu_o M)$(1 T, 4.2 K)	(%)	$\leq$ 4.5
D_{eff}	(μm)	$\leq$ 20
RRR		$\geq$ 150
Unit Length	(km)	$\geq$ 5 km

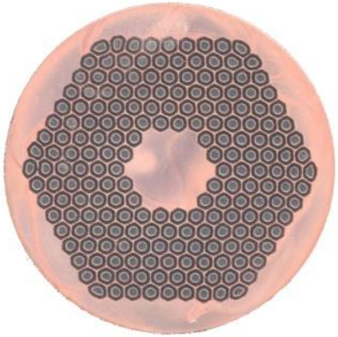
$D_{eff} \leq 20\mu m$ in 0.5 - 1 mm diameter strands

OXFORD INSTRUMENTS

The Business of Science®

- Strand diameter – the issue is relationship to D_{eff}
  - Single Barrier, “ITER” type strands, D_{eff} ~20-30 µm at 0.82 mm (after HT, due to merging)
  - For distributed barrier strands (RRP®, PIT, tube) D_s is tough challenge with a single restack of appreciable weight (large aspect ratio)



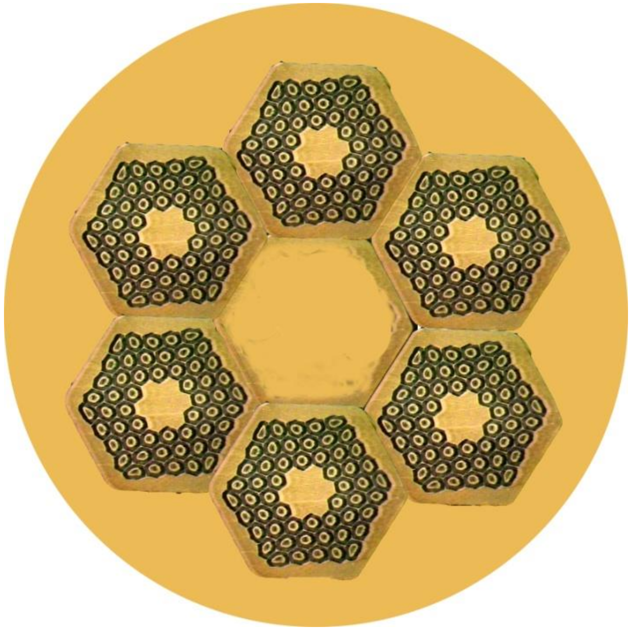


	D_s(stack count) in µm						
wire dia.	**169**	**217**	**271**	**331**	**397**	**469**	**547**
1.0 mm	59	52	47	42	39	35	33
0.9 mm	53	47	42	38	35	32	30
0.85 mm	50	44	40	36	33	30	28
0.8 mm	47	42	37	34	31	28	26
0.7 mm	41	36	33	30	27	25	23
0.6 mm	35	31	28	25	23	21	20
0.5 mm	29	26	23	21	19	18	16

$D_{eff} \leq 20\mu m$ in 0.5 - 1 mm diameter strands

The Business of Science®

- A "double restack" – restacking the restack – can access the smaller D_s at the desired wire size range
  - Need subelements tolerant to a high true strain (i.e. ductile)
  - Difficult to maintain high I_c value, as double restack adds copper to the cross section (i.e. dilutes superconductor fraction)

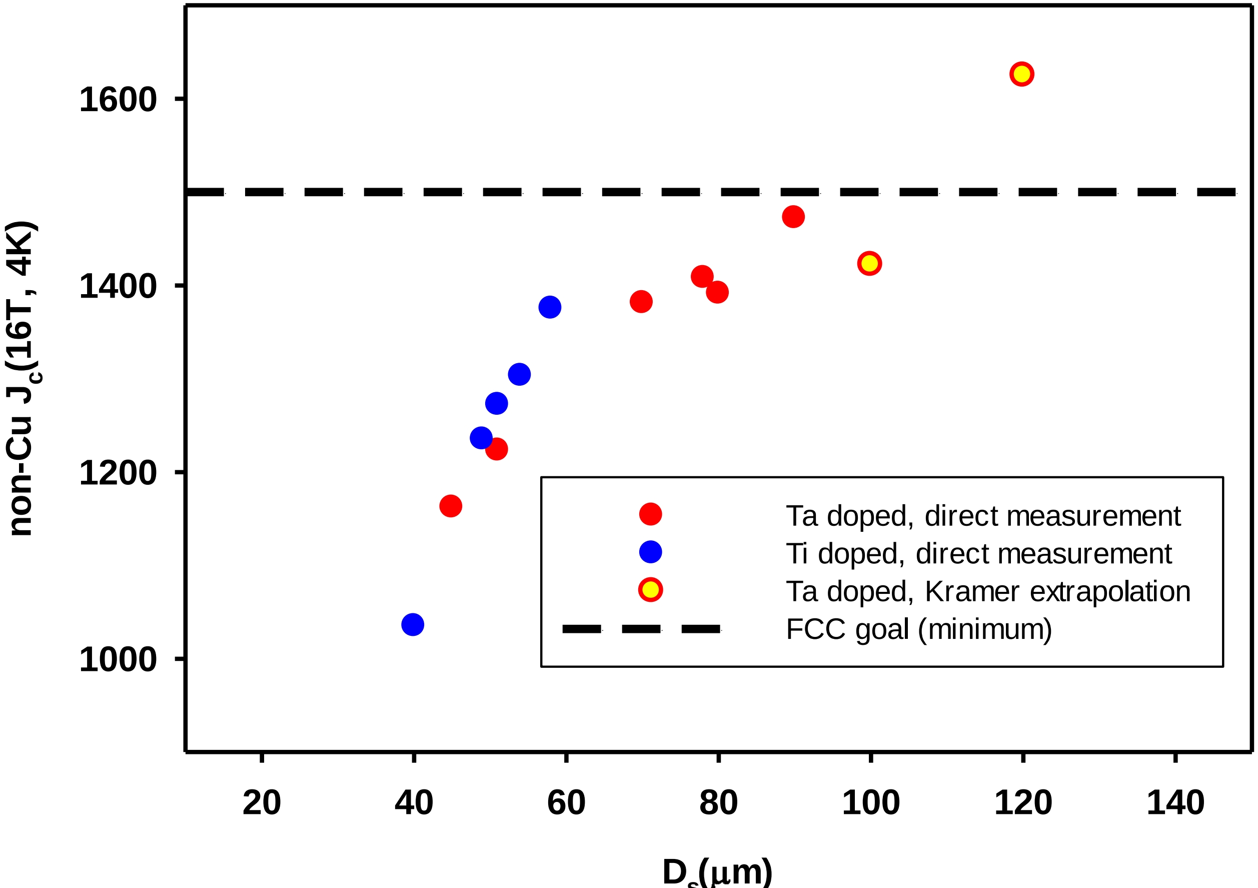


(illustration)
7 stack X 61 stack
$D_s \sim 20\ \mu m$ @ 0.8 mm

Property	Units	Values
Strand diameter	(mm)	0.5 mm to 1.0 mm
J_c(4.2 K, 16 T)	(A/mm^2)	$\geq$ 1500
μ_oM(1 T, 4.2 K)	(mT)	$\leq$ 150
$\sigma(\mu_o$M)(1 T, 4.2 K)	(%)	$\leq$ 4.5
D_{eff}	(μm)	$\leq$ 20
RRR		$\geq$ 150
Unit Length	(km)	$\geq$ 5 km

J_c(4.2 K, 16 T) > 1500 A/mm²

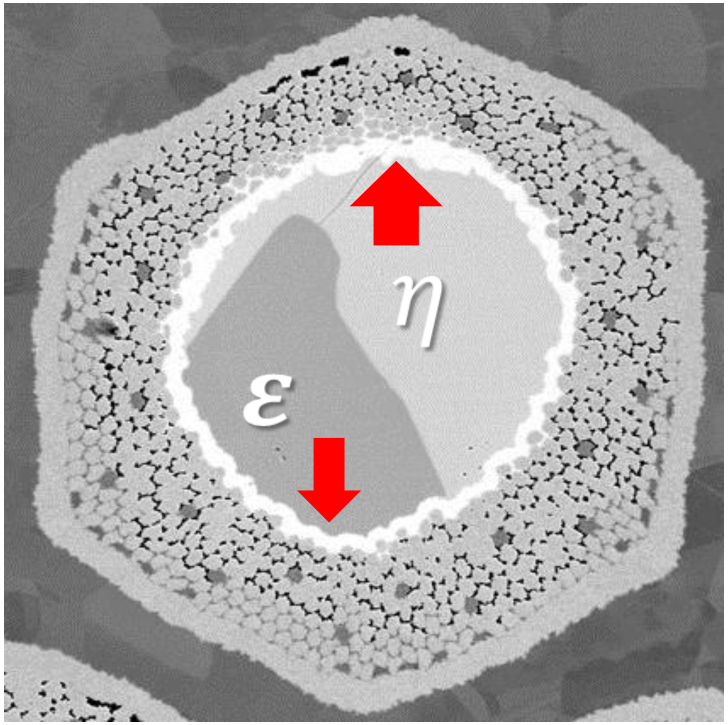
- The most critical parameter – need the J_c to get the field
  - present RRP® design is close – for D_s > 80 μm



"best" 16 T J_c for various RRP across range of D_s

J_c(4.2 K, 16 T) > 1500 A/mm^2

- J_c decreases significantly for D_s below ~50 μm
  - Need better understanding of tin / bronze diffusion and the interaction with Nb-Sn-Cu ternary as $D_s\downarrow$
    - Collaborations with Sanabria (FSU), Pong (LBL)

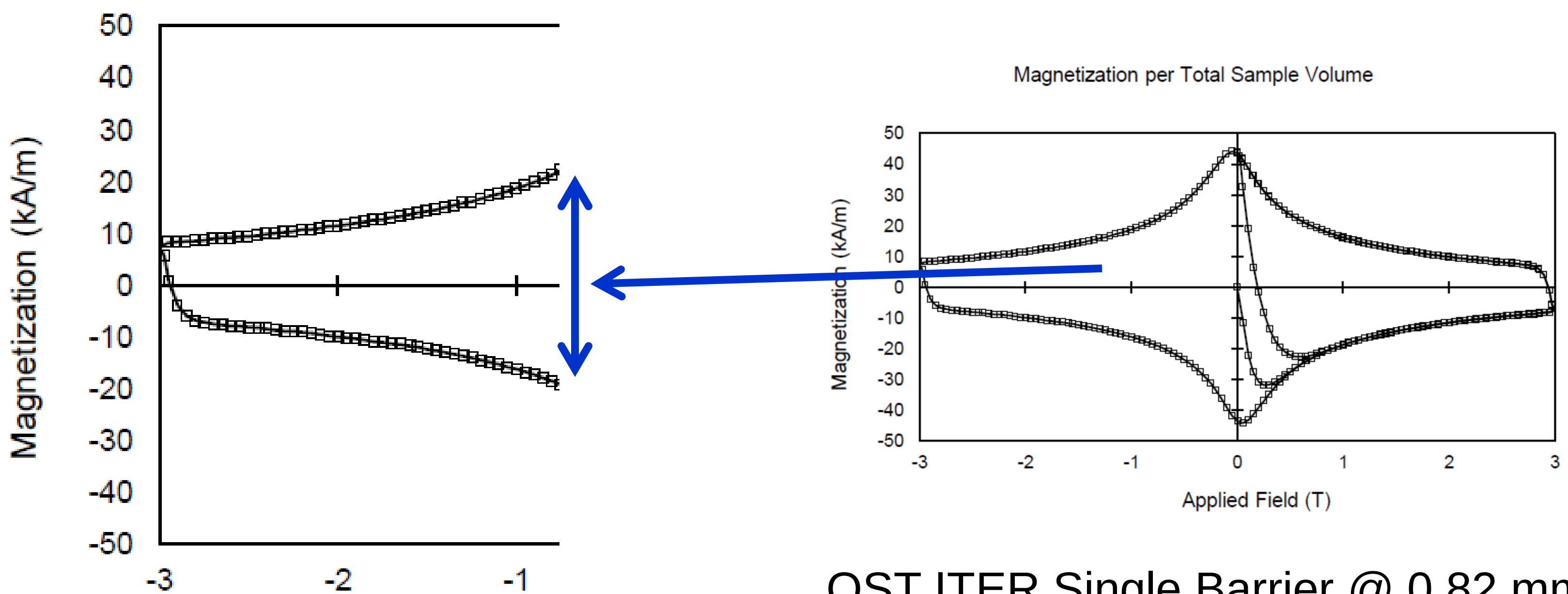


RRP reacted 210°C/48hr + 400°C/48hr, Courtesy of FSU (Peter Lee, Charlie Sanabria)

Property	Units	Values
Strand diameter	(mm)	0.5 mm to 1.0 mm
J_c(4.2 K, 16 T)	(A/mm^2)	≥ 1500
$\mu_o M$(1 T, 4.2 K)	(mT)	≤ 150
$\sigma(\mu_o M)$(1 T, 4.2 K)	(%)	≤ 4.5
D_{eff}	(µm)	≤ 20
RRR		≥ 150
Unit Length	(km)	≥ 5 km

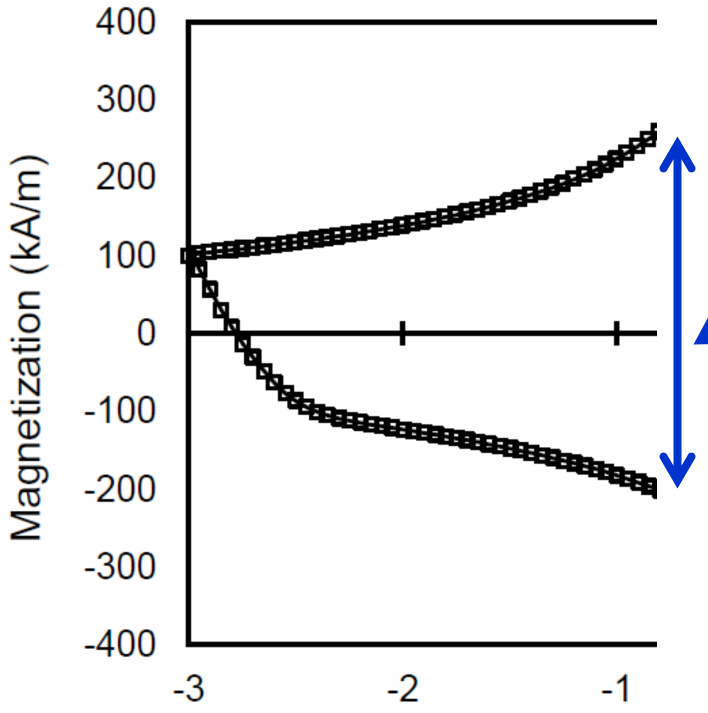
$\mu_o M$(1 T, 4.2 K) < 150mT, $\sigma \leq$ 4.5%

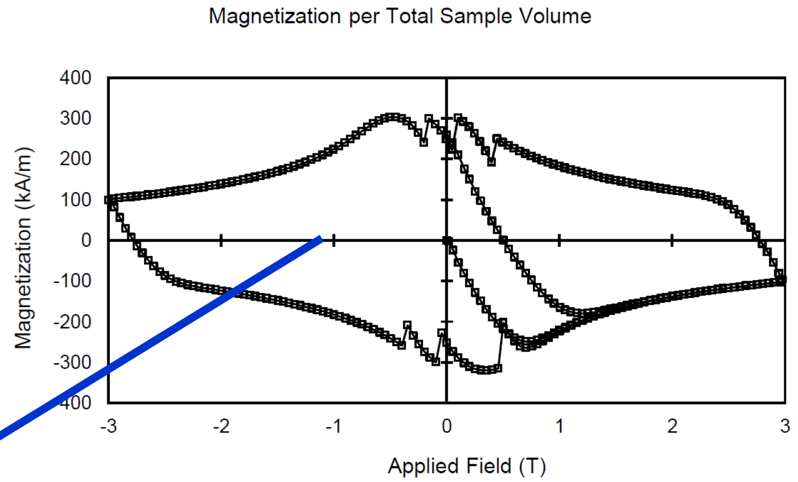
- D_{eff} on order of 20 μm is easier in single barrier strands, but layer J_c is the problem
  - Can layer J_c be increased by APC?
  - σ is a challenge driven by J_c spread



OST ITER Single Barrier @ 0.82 mm

- Distributed barrier RRP® – 3-4x too high
  - Flux jumps also an issue

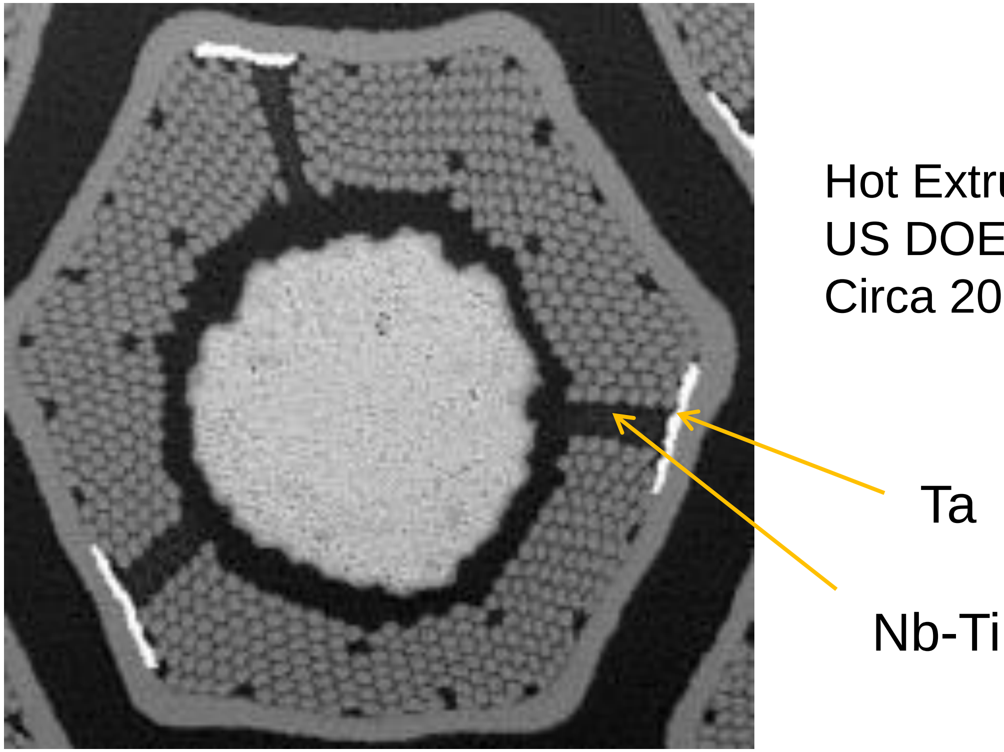




0.778 mm 127 stack,
$D_s \sim 50\ \mu m$

$\mu_o M(1\ T, 4.2\ K) < 150mT, \sigma \leq 4.5\%$

- What if D_s is large but D_{eff} is small?



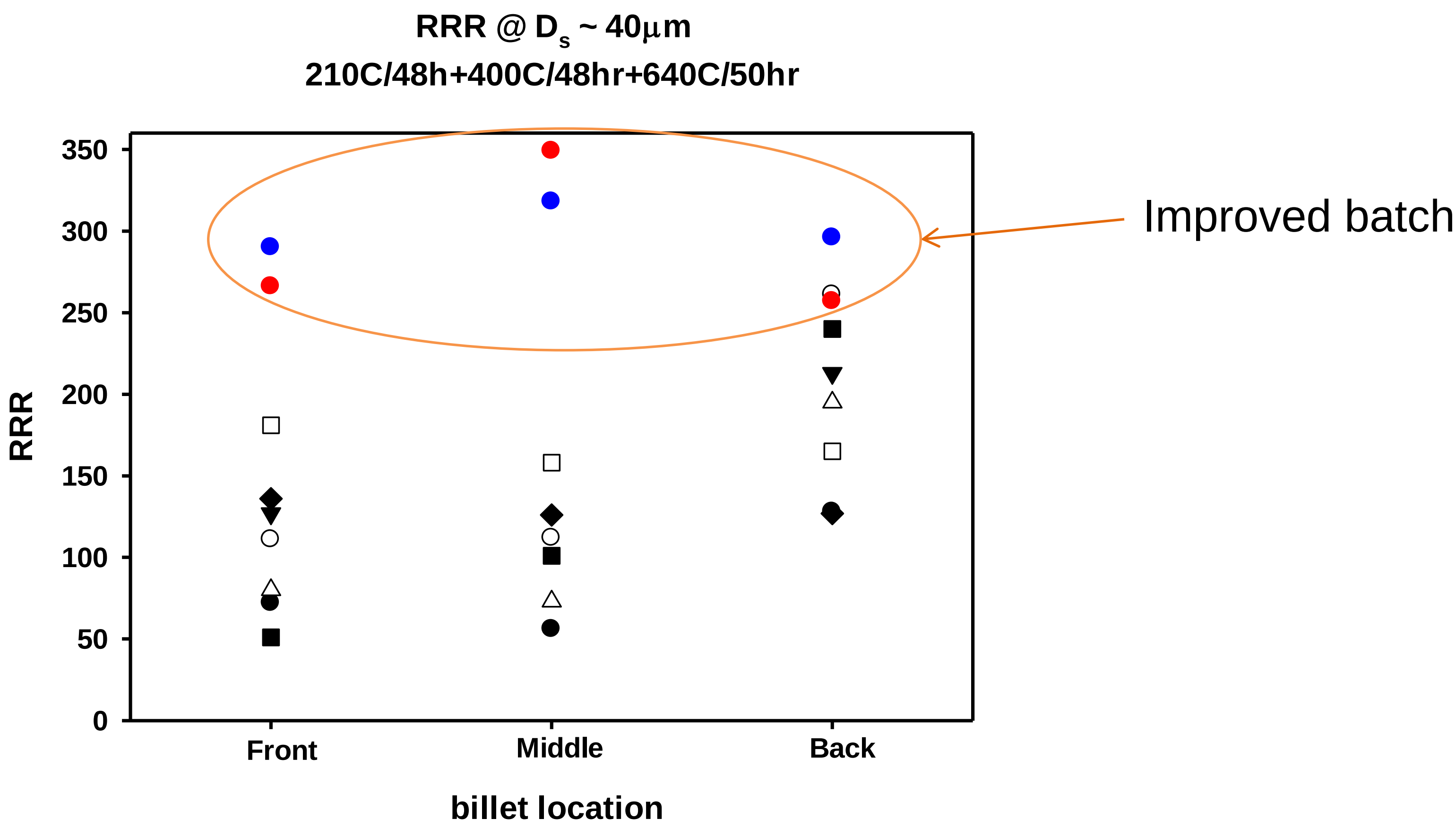
Hot Extruded Rod,
US DOE CDP R&D
Circa 2004

- Depress J_c in low fields - higher B_{c2}
- σ more challenging than single barrier – J_c spread wider

Property	Units	Values
Strand diameter	(mm)	0.5 mm to 1.0 mm
J_c(4.2 K, 16 T)	(A/mm^2)	≥ 1500
$\mu_o M$(1 T, 4.2 K)	(mT)	≤ 150
$\sigma(\mu_o M)$(1 T, 4.2 K)	(%)	≤ 4.5
D_{eff}	(μm)	≤ 20
RRR		≥ 150
Unit Length	(km)	≥ 5 km

RRR > 150

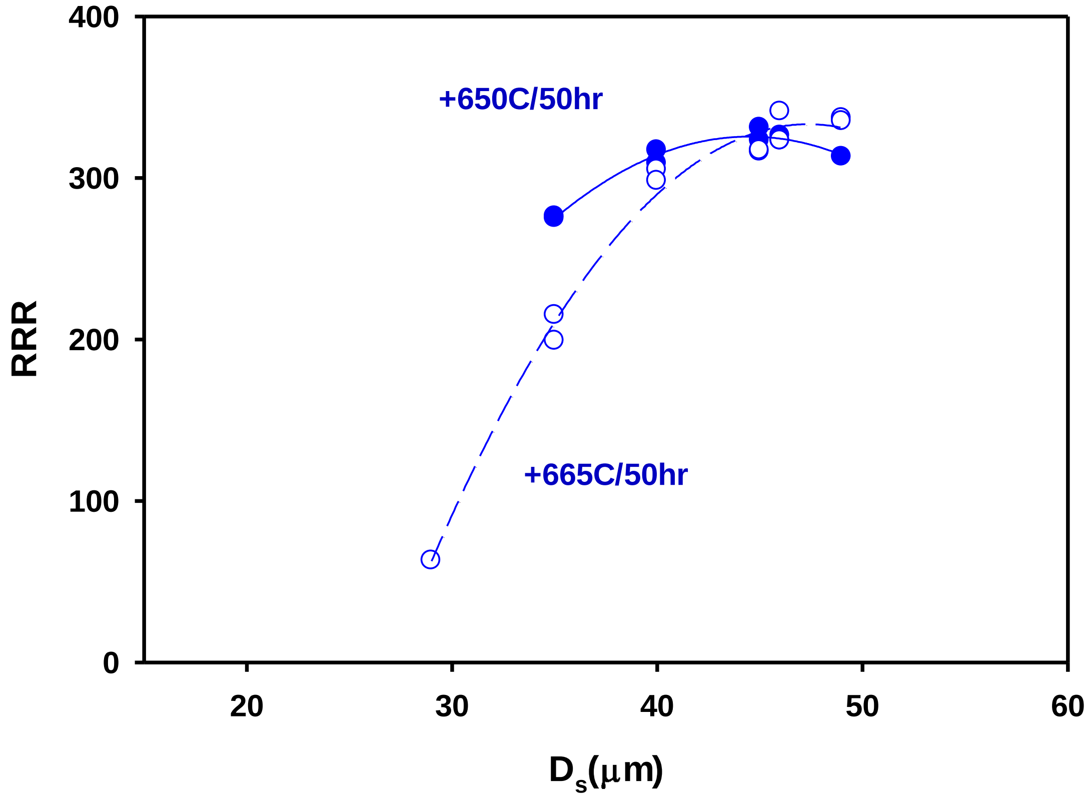
- Improved RRR throughout billet by reducing sources of variation in design and in processing



RRR > 150

- High RRR in small D_s distributed barrier strand still a challenge

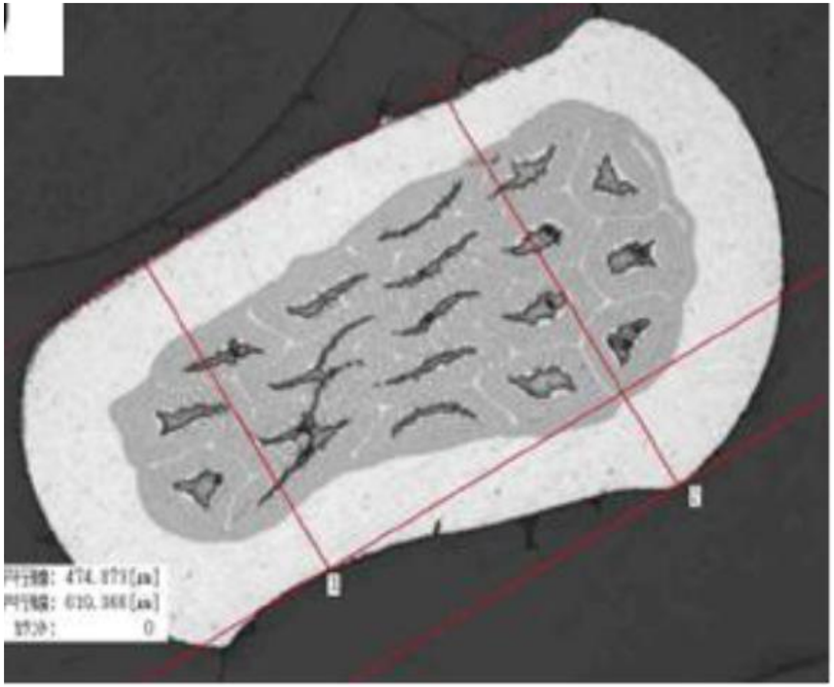
US DOE CDP R&D
Barrier thickness studies
169 stack, Nb:Sn 3.6:1



- Is RRR > 150 in round strand an absolute requirement? What about RRR after cabling? Ever possible to use RRR > 60?

RRR > 150

- Single barrier (ITER style strands) – Ta barriers can remain intact during deformation better than the subelements inside



Extracted strand from CICC, “Challenges and Status of ITER conductor production”, Devred et al

Property	Units	Values
Strand diameter	(mm)	0.5 mm to 1.0 mm
J_c(4.2 K, 16 T)	(A/mm^2)	$\geq$ 1500
μ_oM(1 T, 4.2 K)	(mT)	$\leq$ 150
$\sigma(\mu_o$M)(1 T, 4.2 K)	(%)	$\leq$ 4.5
D_{eff}	(μm)	$\leq$ 20
RRR		$\geq$ 150
Unit Length	(km)	$\geq$ 5 km

Minimum Length > 5 km

- Internal tin = (relatively) small billet volume
- Typical piece length depends on wire diameter?
  - 0.5 mm length 4x 1.0 mm length for same weight
- Need to consider total cost of cable (strand vs. cable yield)
  - As billets are relatively small, long lengths = limited yield
- ITER experience: 70 tons of production, averaged ~6km @ 0.82mm
  - However this was a more "simple" strand

Nb_3Sn for FCC – RRP® vs single barrier

OXFORD INSTRUMENTS

The Business of Science®

Property	Units	Values	RRP®	Single bar.
Strand diameter	(mm)	0.5 mm to 1.0 mm	✓	✓
J_c(4.2 K, 16 T)	(A/mm²)	≥ 1500	close	X
$\mu_o M$(1 T, 4.2 K)	(mT)	≤ 150	X	close?
$\sigma(\mu_o M)$(1 T, 4.2 K)	(%)	≤ 4.5	X	X
D_{eff}	(μm)	≤ 20	X	✓
RRR		≥ 150	?	✓
Unit Length	(km)	≥ 5 km	?	?

Summary

- FCC Nb_3Sn targets present new challenges
- Progress is being made in understanding how to preserve J_c and RRR as D_s is decreased
- New breakthrough needed: keep high layer J_c of RRP® , but with the filament spacing and layout of single barrier strand

Visual metaphor for future FCC strand!