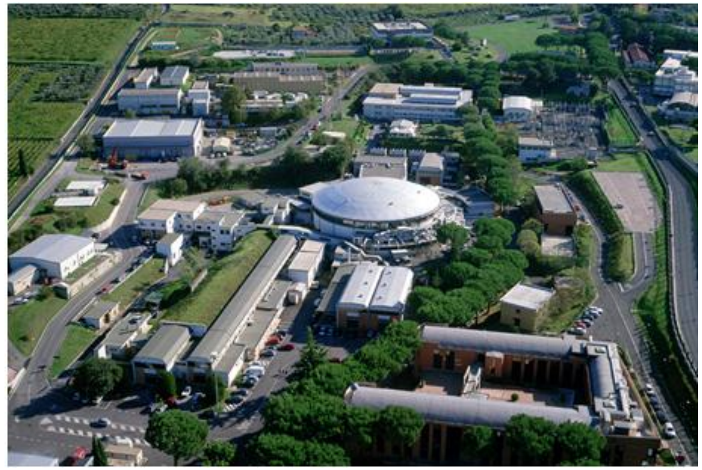

RRP-Nb_3Sn Conductor for the LHC Upgrade Magnets

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Hi-Lumi LARP collaboration meeting

Frascati, Italy Nov 14-16, 2012

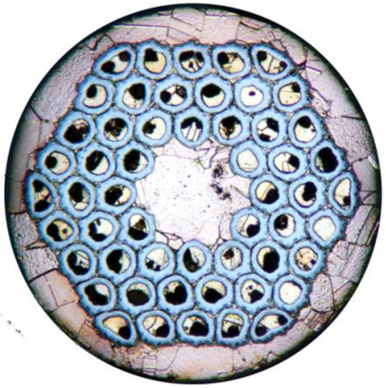
Work supported by the US LHC Accelerator Research Program (LARP) through US Department of Energy

Outline

- Introduction
- RRP® 108/127 Strand
  - OST strand production
- Ti-Ternary Strand
- RRP® strands with smaller filaments
  - 169 and 217 re-stack
- Summary

Introduction

- The LARP program (LHC Accelerator Research Program) goal is the development of high gradient large aperture quadrupoles
- It started with MJR 54/61 conductor from Oxford Superconducting Technology (OST), and transitioned to RRP® 54/61 conductor
- The RRP 54/61 strand is a “production” wire with predictable high J_c at 12 T and 15 T
  - RRR > 200
  - Long piece lengths



- Only drawback: d_s, the sub-element size, is
  - 75 μm for 0.8 mm wire
- Transitioned to 108/127 to reduce filament diameter

Ta-Ternary RRP® 108/127 Wire

- Oxford Superconducting Technology has delivered ~ 190 km of wire to the LARP program for the LQ and HQ magnets ~ 25 billets

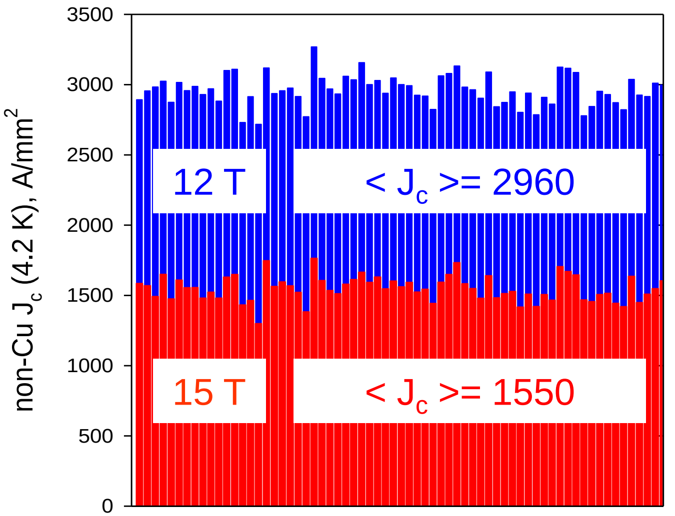
  - Strand Diameter, mm — 0.778
  - J_c(12 T) at 4.2 K, A/mm^2 — > 2650
  - J_c(15 T) at 4.2 K, A/mm^2 — ~ 1400
  - d_s, μm (nominal) — 50
  - Cu-fraction, % — 53 ± 3
  - Cu/non-Cu — 1.13

Wire Reaction schedule

210 °C/72h + 400 °C/48h + 665 °C/50h

J_c of 108/127 wire - 42 billets

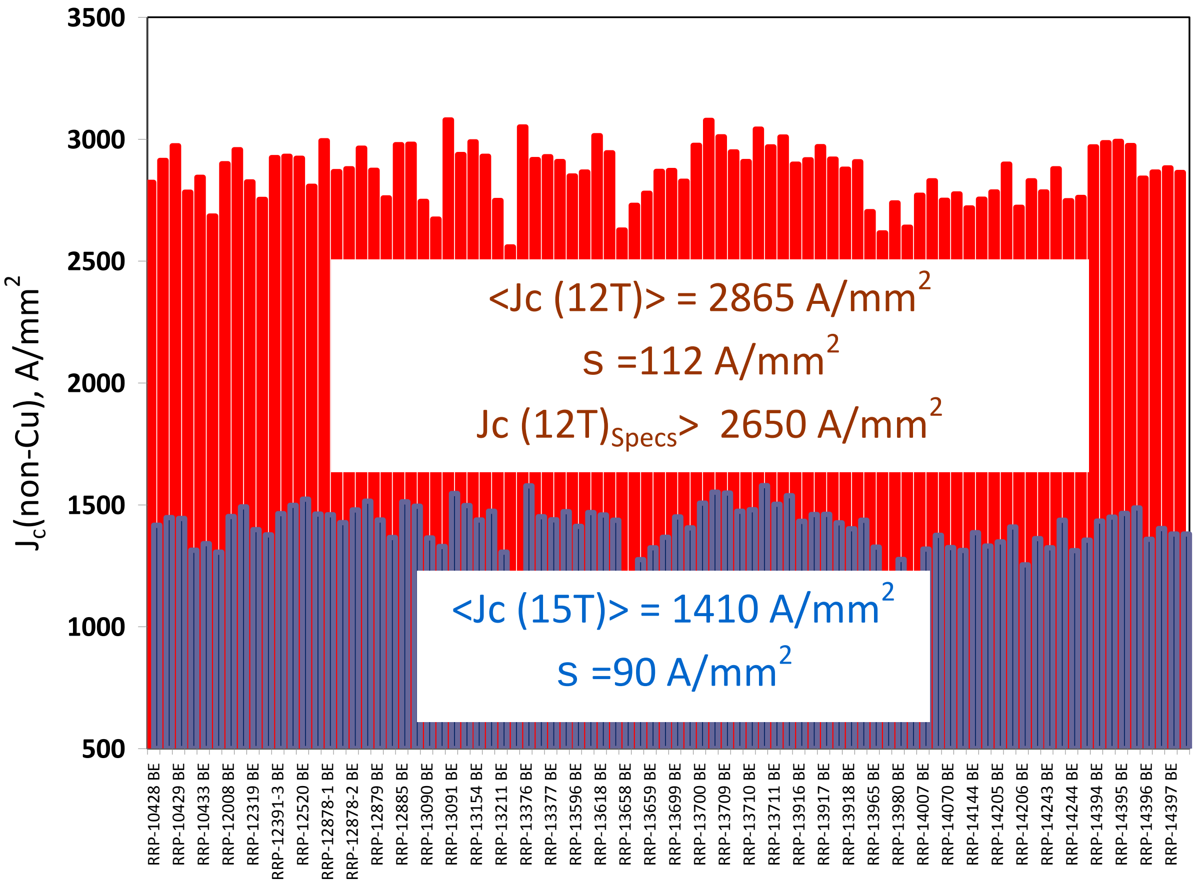
RRP 54/61: 2002-2007



Sampling of billets produced 2002-2007

Courtesy of Jeff Parrell (OST)

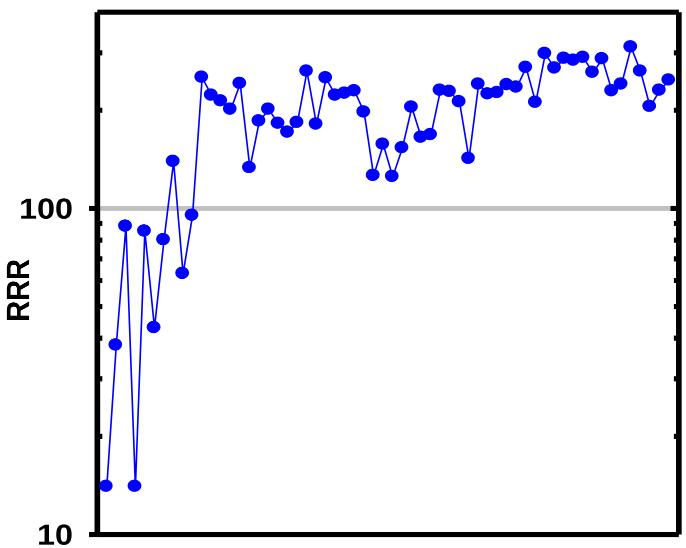
RRP 108/127: 2008-2012



J_c of 108/127 are somewhat lower than for 54/61

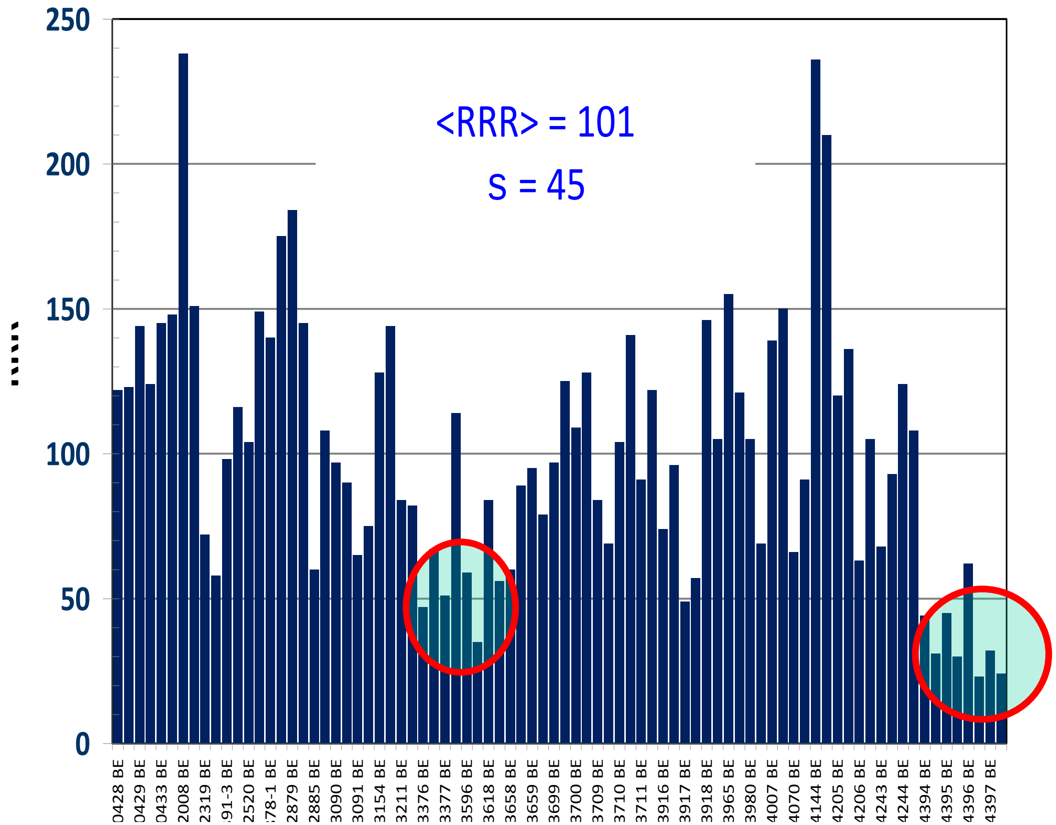
RRP of 108/127 wire

RRP 54/61: 2002-2007



Sampling of billets produced 2002-2007

RRP 108/127: 2008-2012



- Considerable variation in RRR
  - Can be increased by 650 °C/48h reaction
    - ➢ 5% loss in J_c
  - Reducing Sn content by 5%
    - ➢Recent billets show marked increase in RRR

RRR of 108/127 billets with reduced Sn-content

Billet	Jc(12T)	Jc(15T)	RRR
RRP-14752 FE/BE	2864/2914	1524/1535	168/242
RRP-14753 FE/BE	2905/3015	1509/1594	245/213
RRP-14793 FE/BE	2914/2947	1503/1541	114/80
RRP-14794 FE/BE	2956/2933	1525/1531	66/57

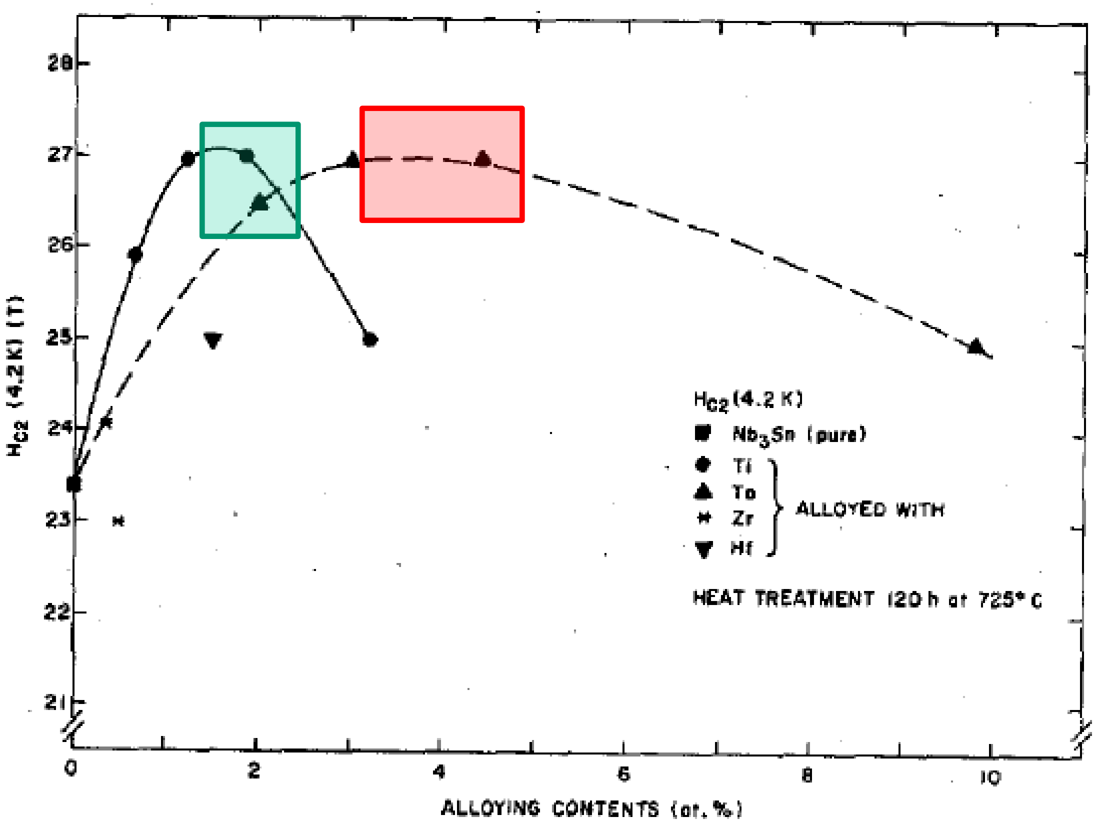
Reduced

Normal

- No difference in J_c
- Significant Improvement in RRR

Ti-Ternary strand

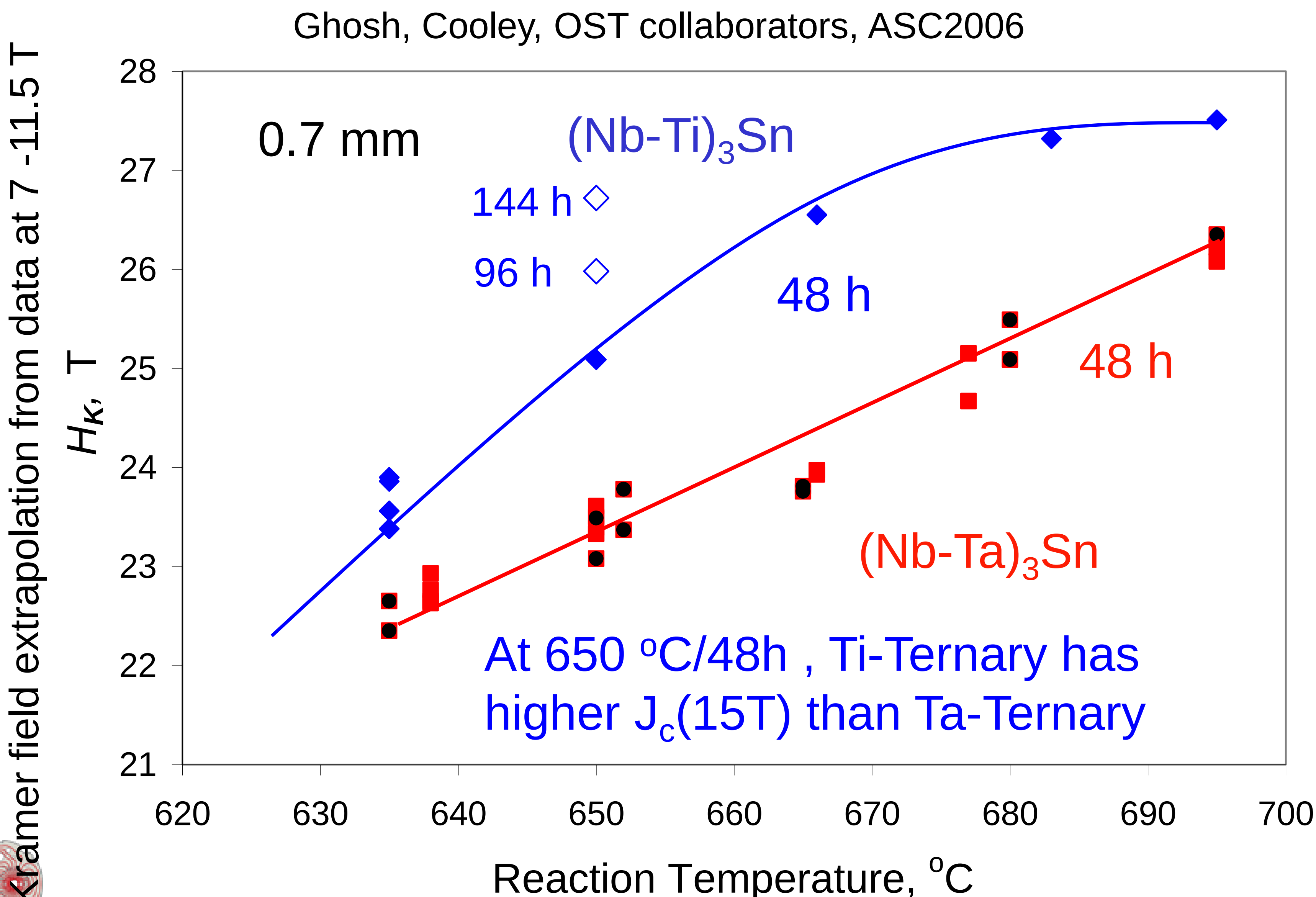
- So far all LARP magnets have been made using Ta - Ternary Nb_3Sn wire (Nb-7.5 wt% Ta) (Nb- 4 a% Ta)
- Ti-doping also increases H_{c2} of the binary alloy



Ti and Ta alloying raises H_{c2} by ~ 4 T at 4 K

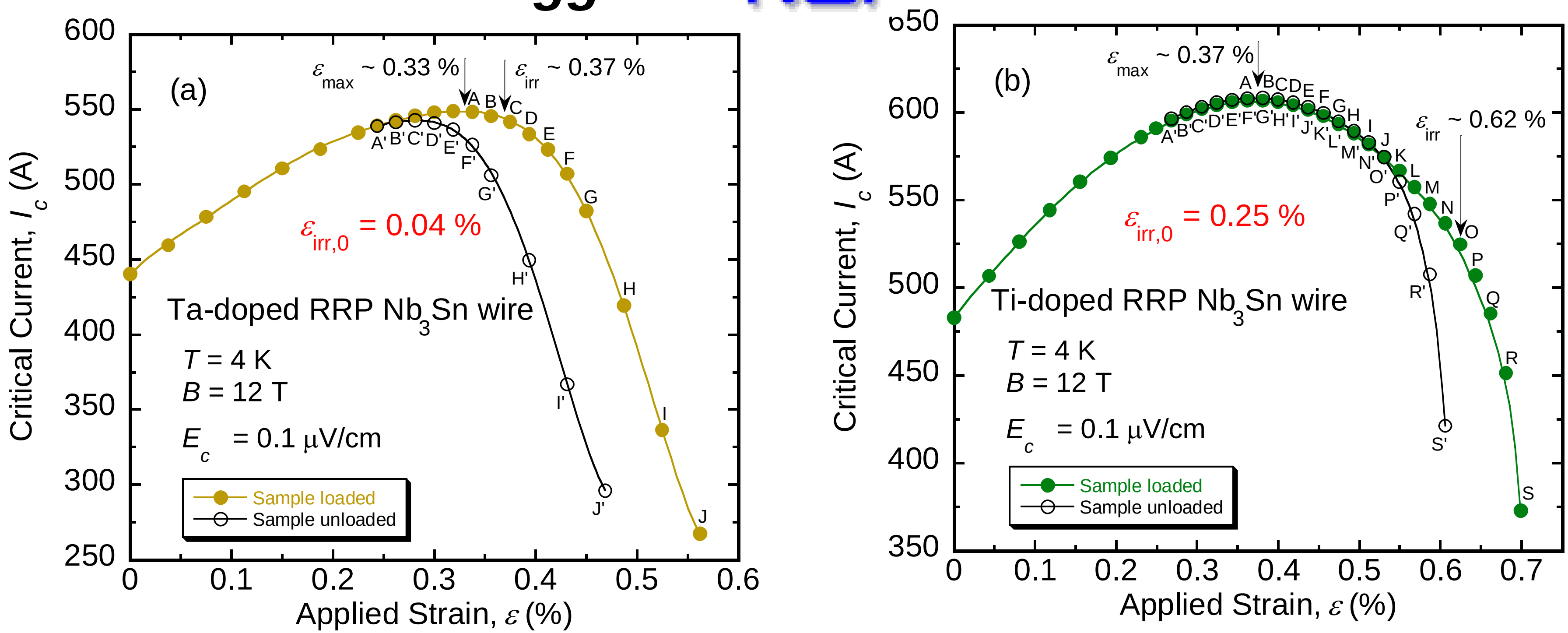
M. Suenaga, *IEEE Trans. on Magnetics, 21,1985*

Ti -Ternary RRP Strand - higher H_K at lower reaction temp.



Ti-Ternary vs. Ta-Ternary: Strain tolerance

Data of N. Cheggour



Ti-doped Nb_3Sn wire more strain tolerant than Ta-doped

Confirmed for RRP® designs 54/61, 90/91, 108/127, 198/217

N. Cheggour, *et al., Supercond. Sci. and Tech*., 20, (2010)

RRP® Ti-Ternary vs. Ta-Ternary

Advantages of Ti-Ternary

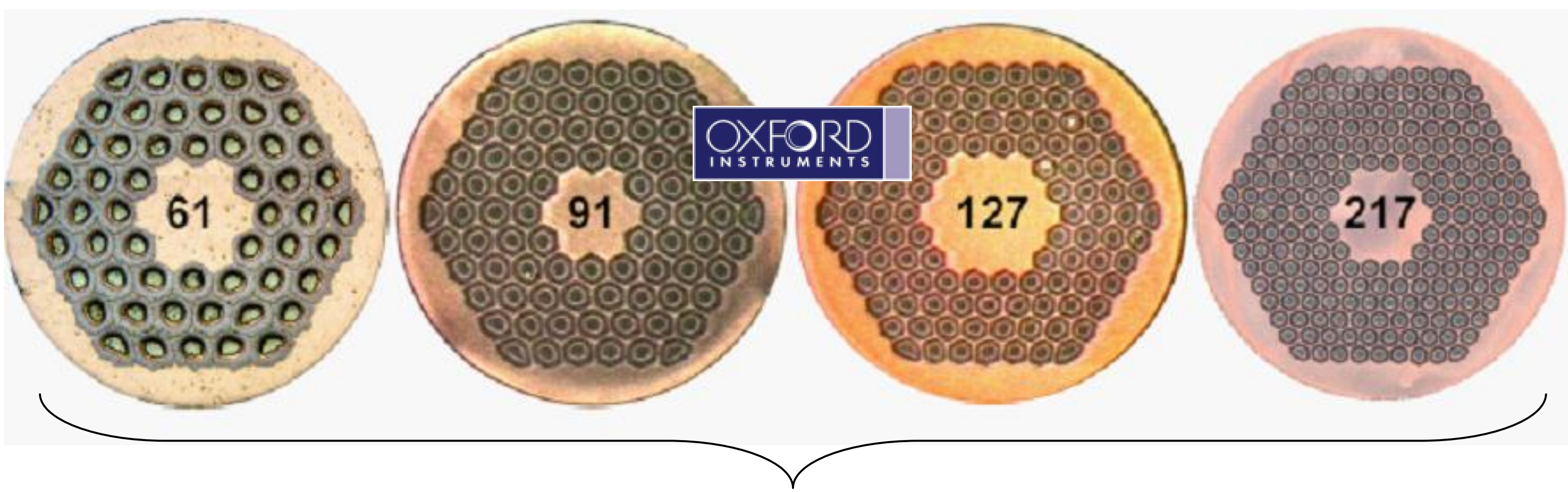
- Does not require Nb-7.5wt% Ta alloy rods
  - Ti introduced by Nb – 47 wt.% Ti rods
- Ti content can be tweaked easily to maximize H_{c2}
- Ti accelerates Nb_3Sn reaction
- At 650 °C/48h , Ti-Ternary has higher J_c(15T) than Ta-Ternary
- Higher strain tolerance
  - i.e. higher irreversible strain limit

Recently OST delivered 112 kg of wire 108/127 Jc (12/15 T): ~ 2900/ 1530 A/mm^2

RRP® strands with smaller filaments

- Smaller sub-elements can minimize flux jumps and improve stability.
- Filament Magnetization decreases

Smaller Filament Size

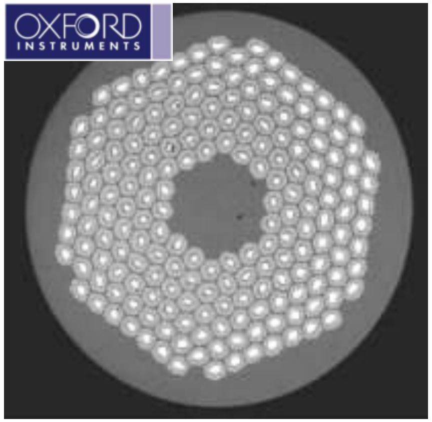


Courtesy of Jeff Parrell (OST)

HEP- Conductor Development Program
Development of 192/217 Design

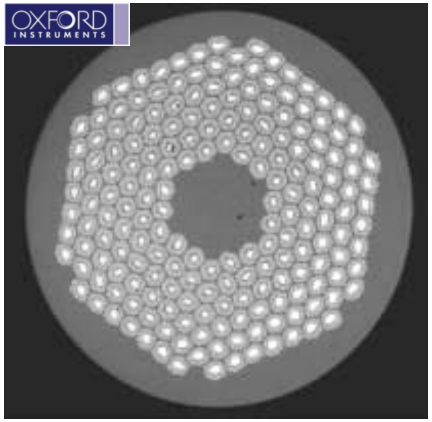
- 192/217 re-stack of 3000 A/mm^2 class sub-elements (high *Nb* and *Sn*-content design used for 54/61 and 108/127) could not be processed to 0.8 mm

- 2400 A/mm^2 class (lower *Nb* and *Sn*-content) processed to 0.8 mm in two long pieces
  - Ti-Ternary
  - *For optimized J_c , RRR very low ~ 8.*
  - ➢ Very difficult to maintain high-J_c and RRR > 50 for smaller filaments

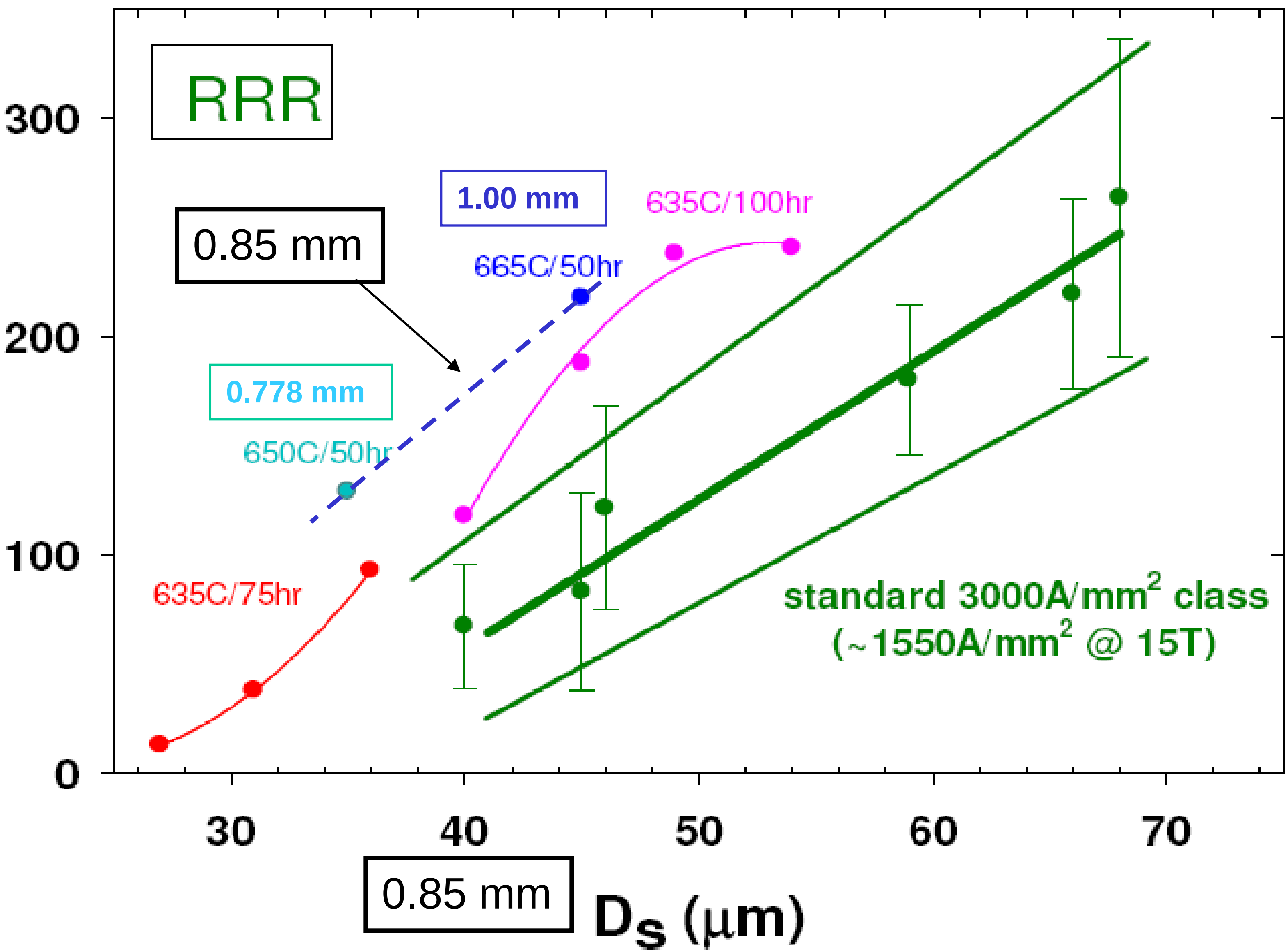


192/217 Re-stack Development

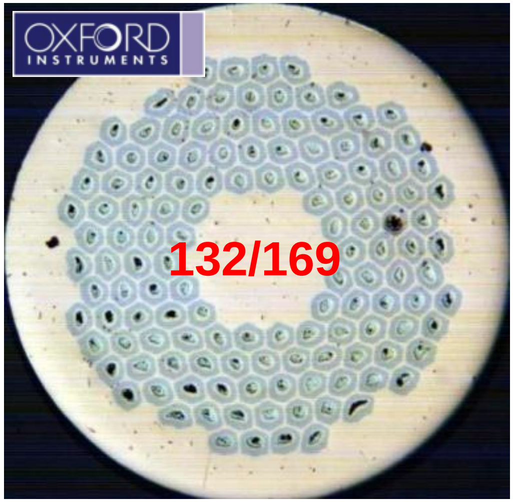
- To increase RRR → new sub-element design
  - ➢ Increase starting *Nb* filament diameter
  - ➢ Control roundness of *Nb* mono-rods
  - ➢ Increase spacing between *Nb* filaments
  - ➢ Increase barrier thickness
  - New 2700 A/mm^2 class conductor being fabricated
- First results from OST for wire fabricated with 30% thicker barrier -- 0.778 mm diameter
- 650C/ 50 h
  - J_c (12T) = 2590 A/mm^2
  - J_c (15T) = 1350 A/mm^2
  - RRR 118-129



CDP - New RRP 192/217 (Ti-doped)



Another Option- 169 re-stack



- 10 km delivered to CERN
  - Ti-Ternary, 1.0 mm
  - d ~ 57 μm
  - J_c(12T) ~ 3050 A/mm²
  - J_c(15T) ~ 1680 A/mm²
  - RRR 140 – 200
- 1.0 mm wire when drawn down to 0.80 mm shows very good properties
  - d ~ 46 μm
  - Jc(12T) ~ 3130 A/mm2
  - Jc(15T) ~ 1630 A/mm2
  - RRR ~ 100

LARP

Sub-element (Filament) diameter, μm

$$d_s = \frac{D_w}{\sqrt{N(1+R)}}$$

R=Cu/Non-Cu=1.2 , 45.5% SC, 54.5 % Cu

Strand Design	54/61	84/91	108/127	150/169	198/217	252/271	312/331
	# of Sub-elements						
D_w, mm	**54**	**84**	**108**	**150**	**198**	**252**	**312**
1.0	92	74	65	55	48	42	38
0.85	78	63	55	47	41	36	32
0.778	71	57	50	43	37	33	30
0.7	64	52	45	39	34	30	27

35 kg Billet

Presently, sub-element rod sizes are very small for assembly of 217. Larger diameter re-stack billets will make it easier to control production of 217, and enable re-stacks with higher number of sub-elements.

Summary

- Present Status of RRP wire
  - 108/127 design has good J_c properties
    - RRR being controlled by reducing Sn-content without loss of Jc
  - 132/169 or 150/169 is an emerging option for wire diameter > 0.80 mm or 0.85 mm
  - Ti- ternary allows lower reaction temperature for equivalent J_c and higher H_K than the Ta-ternary
    - Higher J_c at 15 T
  - 217 Re-stack strand with thicker barrier is being developed
    - scale-up to 60 kg will further enable this re-stack design

End of Presentation