A New Generation Nb$_3$Sn wire, and the Prospects for its Use in Particle Accelerators

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Presentation Outline

• Accelerator magnet applications for Nb$_3$Sn
  --LHC Luminosity Upgrade
  --LHC Energy Upgrade
• Conductor Development Program Status and Plans
  --Performance improvements (Jc and D$_{eff}$)
  --Cost reductions
  --New conductors
Possible LHC upgrades would require large quantities of Nb₃Sn wire

• 20 tons for the interaction region quadrupole upgrade (timeframe--2010)

• As much as 500 tons for an energy upgrade to 14 TeV (timeframe--?)

• Conductor R&D and production scaleup are required to meet the performance and quantity requirements.
Goals and Target Specifications have been developed in collaboration with the CDG

- Goal: Provide cost-effective, high-performance superconductor required for luminosity upgrades and for the next generation high-energy physics colliders.

- Target specifications for the HEP conductor include:
  -- $J_c$ (noncopper, 12T, 4.2 K): 3000 A/mm$^2$ (1500 @ 15 T)
  -- Effective filament size: 40 microns or less
  -- Piece length: Greater than 10,000 m in wire diam. of 0.3-1.0 mm
  -- Heat treatment times: Less than 200 hr; target is 50 hr for wind and react
  -- Wire cost: Less than $1.50/kA-m (12 T, 4.2 K)
Steps toward improvements in Jc

1. Optimize use of available space
   --OST and OKAS focus during first 2 years R&D
   --a Jc increase from 2000 to 3000 A/mm² (12 T, 4.2 K) has been achieved

2. Optimize heat treatment
   --high Nb, Sn composites require different heat treatments (OST-MJR Jc increased from 2600 to 2900 A/mm²)
   --Lab/Univ support includes microstructure evolution studies and improved Ic testing

3. Refine grain size in Nb₃Sn
OST has achieved world record Jc values for Nb₃Sn made by two processes (LTSW Nov’02)
Rod process has replaced MJR at OST

- $J_c$ performance as good or better than MJR
- Much better piece length than MJR
- Use of rods and extrusion instead of sheets and all-cold drawing makes yield more predictable
- $J_c$ (12 T, 4.2) ~3000 A/mm² (one short sample over 3000 A/mm² at OST)
OST RRP Wire--HT and Test at LBNL

- OST B6555, 49%Cu
- HT 650 C, 200hr
- RRR=15
- $D_{\text{eff}} \sim 100 \text{ µm}$
- Stable to 58 µV/m

\[12.38 \text{T}, 4.2 \text{K}\]
\[I_c = 776 \text{A}\]
\[J_c = 3,016 \text{ A/mm}^2 (0.803 \text{mm})\]
\[J_c = 2,900 \text{ A/mm}^2 (0.819 \text{mm})\]

10^{-12} \text{ ohm-cm}
OI-ST 3000 A/mm² Strand: New $J_{csc}$

--From P. Lee, PAC’03

Non-Cu:A15 ratio from image analysis of high resolution FESEM images of 4 sub-elements

OI-ST RRP
3000 A/mm²
(12T, 4.2K)
OST Nb$_3$Sn wire #6581 (higher Nb$_3$Sn %):
Axial strain effect at 4 K & 16.5 T--data from Ekin and Cheggour, NIST

$\phi$ 0.5 mm; Cu-plated to ratio 3:1
($\phi \sim 0.77$ mm)

- $\varepsilon_{\text{max}} \sim 0.25 \%$
- $\varepsilon_{\text{irr}} \sim 0.65 \%$
- $\varepsilon_{\text{ult}} \sim 0.73 \%$

$A'B'C'D'E'F'G'H'I'\quad T = 4 \ K \quad B = 16.5 \ T$
OST has completed production quantities of high Jc wires for use in Dipole HD-1

- **MJR process** (50 kg delivered Aug 2002, meets specification)
  - $J_c$ (12T, 4.2K) $> 2250$ A/mm$^2$
  - RRR (copper residual resistivity ratio) $> 2$
  - Yield: $> 72\%$ piece lengths $> 250$ m
  - $D_{eff} < 100$ microns

- **RRP process** (50 kg delivered Jan 2003, exceeds $J_c$ spec.)
  - $J_c > 2750$ A/mm$^2$; best value $> 3000$ A/mm$^2$
  - RRR $> 15$
  - Yield: 86\% piece lengths $> 250$ m
  - $D_{eff} < 100$ microns
Comparison of low, moderate and high Jc subelements

- Low--filaments are discreet and not interconnected; diffusion barrier is Ta

- Moderate--Filaments are discreet, but interconnected, diffusion barrier is Ta or Nb

- High--filaments have coalesced to form a monolithic structure, diffusion barrier is Nb
Magnetization loop for high Jc wire shows evidence for partial flux jumps

OST wire with distributed barrier; Jc=3000 A/mm², D_{eff}=80 microns
Limits to increasing Jc by increasing Nb and Sn volume fractions

- Large magnetization
- Flux jump instabilities
- Lower matrix RRR
- Fabrication issues
- Filament dissolution during reaction step
Main emphasis in FY04--reduce $D_{\text{eff}}$

- Increase number of subelements (OST, Supergenics SBIRs)

- Use fins to subdivide subelements (OKAS, Supergenics, OST)

- PIT conductor fabrication (Shape Metal Industries, Supercon)
More Sub-Elements Required . . or

- Large number of sub-elements needed – with associated stacking problems – unless the subelements are sub-divided
- Even so, > 36 subelements required

*From P. Lee, PAC’03*
Key task for reduced $D_{\text{eff}}$ is to determine methods (and limits) for restacks

Subelement restack issues include:

--Single or double restack
--Bonding
--Subelement/barrier distortion
--Matching hardness of components
--Sn rod size for HER

OKAS restack with 54 subelements, 3 fins
OST R&D program (FY04)

- Demonstrate HER process for making high $J_c$, low $D_{eff}$ wire
- Distributed barrier design (highest $J_c$, good $D_{eff}$)
  -- 127 subelements
  -- $D_{eff} = 40 \, \mu m, 0.6 \, mm$ diam.
- Cost reduction/improved piece lengths
- Improved RRR

Hot extruded rod with 18 holes, ready for loading Sn rods
OKAS R&D Program

- Fabricate reduced $D_{\text{eff}}$ wire using fins
- Improve drawability of the OKAS internal tin wire
  
  (scaleup work for ITER--will benefit HEP as well)
A New Approach for reducing Deff without increasing number of subelements: fins

- SBIR work by Supergenics/OKAS
  - radial fins to prevent filaments from coalescing
  - short barrier section to prevent reaction on Nb barrier
  - add more fins to further subdivide Nb₃Sn
  - penalty is only 0.4-0.8 % area fraction per fin
  - Ta 40 wt% Nb alloy
Fin approach is continuing at both Supergenics and OKAS

- **OKAS**
  - three radial fins
  - Ta 40 wt % Nb alloy
  - add more fins to further subdivide Nb₃Sn
  - use as subelement for restack

- **Should be applicable to many fabrication processes**
Features of Fin Reaction – Electron Backscatter--data from P. Lee

- Cu(Sn) Core
- Fully Reacted
- Voids
- Partially Reacted
- Fin
- Nb₃Sn Filaments

Grain Boundary
Compositional Variation
Further improvements must come from process scale-up. New ITER?
Conductor Costs for High Field Accelerator Magnets (12T, 4.2K)

- \( \text{Nb}_3\text{Sn (OST RRP)} \) -- $5.75/kA-m
- \( \text{Nb}_3\text{Sn (MJR)} \) -- $7.74/kA-m
- \( \text{Nb}_3\text{Sn (PIT)} \) -- $28.94/kA-m
- \( \text{Bi-2212 (PIT)} \) -- $57.00/kA-m

These prices are for small, custom-processed orders
U.S. DOE funding for conductor R&D

• $500 K/year for HEP base program (starting in 2000 and continuing in FY05)
  – Nb$_3$Sn R&D at OST and OKAS
• $2000K--2500K/year for HEP and OFE SBIR program
  – Nb$_3$Sn R&D at Supercon, Supergenics, Hypertech, Accelerator Technology Corp, Innovare, Superconducting Systems, Alabama Cryogenic
  – Nb3Al R&D at Hypertech, Global R&D, Innovare
  – Insulation R&D at CTD and MCT
Cost reduction tasks for HEP R&D program include

- **Billet scale-up**
  - OST HER
  - OKAS restack rod

- **Improved raw materials**
  - Replacement for Sn-Ti alloy
  - Ductile diffusion barriers

- Note: We rely on the ITER program to provide the large volume production capability for Nb$_3$Sn
Bi-2212 round wire shows promise for accelerator magnets

- $J_c(12T, \ 4.2K, \ \text{non-silver}) > 2000 \ \text{A/mm}^2$ in new material (Showa, OST)
- Long lengths (> 1500 m) are being produced
- New result: 30 strand cable; $I_c = 6.8 \ \text{kA at 6 T}$
- React/wind (BNL) and Wind/react (LBNL) coils will be evaluated
Steady progress continues toward program goals

- **Long Range Goals**
  - $J_c = 3000 \text{ A/mm}^2$
  - $D_{eff} = 40 \text{ microns or less}$
  - Piece length $> 10,000 \text{ m}$
  - Heat treatment $< 400 \text{ hr}$
  - Cost: $< $1.50/kA-m (12 T)

- **Progress**
  - $J_c = 3000 \text{ A/mm}^2$ (FY03)
  - Proof of principle shown; practical demos in progress
  - 250-1500m for both MJR and RRP internal Sn processes
  - 150 hr
  - $5.50/kA-m$ (RRP)