The FCC Conductor Development Plan
A. Ballarino, CERN

FCC Week 2016
ROME 11-15 April 2016

Sotto l’alto patronato del Presidente della Repubblica
Outline

- $\text{Nb}_3\text{Sn}$ for FCC
  - $\text{Nb}_3\text{Sn}$ for FCC vs ITER conductor
  - $\text{Nb}_3\text{Sn}$ for FCC vs Hi-Lumi LHC conductor
- $\text{Nb}_3\text{Sn}$ Conductor Development Program
- HTS potentials
- Conclusions
**TF Strand Zoo: Nb$_3$Sn**

- BAS (Br; EU)
  - [Flag](image)
- ChMP (Br; RF)
  - [Flag](image)
- Hitachi (Br; JA)
  - [Flag](image)
- Jastec (Br; JA)
  - [Flag](image)
- KAT (IT; KO)
  - [Flag](image)
- Luvata (IT; US)
  - [Flag](image)
- OST (IT; EU & US)
  - [Flag](image)
- WST (IT; CN)
  - [Flag](image)

Worldwide production increased from 15 tons/year up to 100 tons/year

~ 500 tons

\[ Jc = 800 \text{ A/mm}^2 \ (4.2 \text{ K, 12 T}) \]
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of $L_{\text{peak}} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with levelling, allowing:

An integrated luminosity of 250 fb$^{-1}$ per year, enabling the goal of $L_{\text{int}} = 3000 \text{ fb}^{-1}$ twelve years after the upgrade. This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime. **Extension of Physics reach.**

Timeline:
- **Design Study & R&D (2010-2016)**
- **Construction and Installation (2017-2025)**
- **Commissioning and Physics (2026 - 2035~40)**
LHC High Luminosity Upgrade

$\text{Nb}_3\text{Sn}$ for the first time in an operating accelerator

L. Rossi, CERN
**Nb₃Sn industrial wires**

- **Bronze Route**
  - Diffusion barrier
  - Nb
  - Bronze
  - Cu

- **Internal Tin**
  - Diffusion barrier
  - Sn
  - Nb
  - Cu

- **Powder In Tube**
  - Sn rich powder
  - Nb
  - Cu

Small filaments (Φ < 5 μm) Jc limited (~ 1-1.2 kA/mm² @ 12 T, 4.2 K) by the solubility of Sn in Cu (~15.5 wt %)

**High Jc Nb₃Sn wires for accelerator magnets**
High field Nb$_3$Sn: state-of-the-art of Hi-Lumi Nb$_3$Sn industrial production

- **PIT**(Bruker) and **RRP** (OST) technology

- Ternary (NbTi)$_3$Sn or (NbTa)$_3$Sn compounds → Bc$_2$ enhanced by increasing $\rho_n$ without sacrificing Tc and workability (1-2 % at Ti and 2-4 at % Ta)

- **Multi-filamentary wires**
  $\Phi = 0.7$ mm and 0.85 mm, filaments/sub-elements size $\sim 40$-$50$ $\mu$m

- Total quantity: $\sim 20$ tons
Nb$_3$Sn for Hi-Lumi LHC: $J_c$

Graph showing the relationship between $J_c$ at 4.2 K (A/mm$^2$) and magnetic field (T). The graph includes data points for LHC High Luminosity, with values of 2450 A/mm$^2$ at 12 T and 1000 A/mm$^2$ at 16 T. Images of samples labeled RRP and PIT are displayed.
## Measurements – Nb₃Sn for Hi-Lumi

### \( J_c \) & \( B_{c2} \) @ 4.22 K

<table>
<thead>
<tr>
<th>Sub-Element Shape</th>
<th>Layout</th>
<th>RRR</th>
<th>( J_c ) (12 T), RMS [A/mm²]</th>
<th>( J_c ) (15 T), RMS [A/mm²]</th>
<th>( J_c ) (16 T), RMS [A/mm²]</th>
<th>( J_c ) (17 T), RMS [A/mm²]</th>
<th>( B_{c2} ), RMS [T]</th>
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</thead>
<tbody>
<tr>
<td>0.7 mm RRP</td>
<td>132/169</td>
<td>41 μm</td>
<td>185, 64</td>
<td>2508, (2450) 125</td>
<td>1232, 81</td>
<td>924, 70</td>
<td>670, 60</td>
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<td></td>
<td>144/169</td>
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<td>172, 30</td>
<td>2408, 146</td>
<td>1186, 104</td>
<td>888, 91</td>
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<tr>
<td>0.85 mm RRP</td>
<td>132/169</td>
<td>50 μm</td>
<td>235, 52</td>
<td>2777, (2450) 81</td>
<td>1427, (1280) 55</td>
<td>1091, 48</td>
<td>814, 43</td>
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<tr>
<td>0.7 mm PIT</td>
<td>114</td>
<td>44 μm</td>
<td>138, 34</td>
<td>2426, (2450) 66</td>
<td>1357, 50</td>
<td>1089, 45</td>
<td>845, 40</td>
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<td></td>
<td>120</td>
<td></td>
<td>103, 50</td>
<td>2302, 101</td>
<td>1284, 65</td>
<td>1027, 57</td>
<td>804, 49</td>
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<tr>
<td>0.85 mm PIT</td>
<td>192</td>
<td>41 μm</td>
<td>175, 30</td>
<td>2340, (2450) 53</td>
<td>1306, (1280) 41</td>
<td>1047, 37</td>
<td>822, 34</td>
</tr>
</tbody>
</table>

This morning talks on Hi-Lumi conductor by B. Bordini and L. Cooley.
**Nb₃Sn Hi-Lumi wire challenges: Deff**

\( T = 1.9 \text{ K} \)

\( \Phi = 0.7 \text{ mm (11 T Dipole Project)} \)

- Reduce filaments size to reduce magnetization
- M-loop width (0.54 T, 1.9 K) < 30 mT
- Max spread around average ± 4.5%
- Trade-off between \( J_c \) and \( D_{eff} \)

Measurements @ CERN

A. Ballarino, CERN
Nb$_3$Sn Hi-Lumi wire challenges: RRR

New generation of PIT Nb$_3$Sn for HE Physics

Nb barrier that protects the other shell of copper. It:
1) prevents RRR degradation after deformation;
2) enables use of higher Sn content

CERN-Bruker EAS R&D collaboration
Mechanical properties of PIT and RRP wires appropriate for cabling → Ic degradation of wire < 5 %, RRR maintained above 100
Nb$_3$Sn for FCC: challenges

- Higher $J_c$ at 16 T
- Aggressive $J_c$ and small filaments size
- Industrial fabrication and scale-up for large scale production
- Cost effectives
## Final Targets for FCC Conductor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter</td>
<td>mm</td>
<td>~1</td>
</tr>
<tr>
<td>Non-Cu Jc (16 T, 4.2 K)*</td>
<td>A/mm²</td>
<td>≥1500</td>
</tr>
<tr>
<td>μµΔM (1 T, 4.2 K)</td>
<td>mT</td>
<td>≤150</td>
</tr>
<tr>
<td>σ(μµΔM) (1 T, 4.2 K)</td>
<td>%</td>
<td>≤4.5</td>
</tr>
<tr>
<td>Deff</td>
<td>µm</td>
<td>≤20</td>
</tr>
<tr>
<td>RRR</td>
<td>-</td>
<td>≥150</td>
</tr>
<tr>
<td>Unit length</td>
<td>km</td>
<td>≥5</td>
</tr>
<tr>
<td>Cost</td>
<td>Euro/kA m**</td>
<td>~5</td>
</tr>
</tbody>
</table>

*Je ~ 600 A/mm²
*Cu:non Cu ~ 1

** 16 T, 4.2 K

Targets derived from the larger context of magnet design requirements

A. Ballarino, CERN
\( \text{Nb}_3\text{Sn} - J_c \text{ Target for FCC} \)

Graph showing the relationship between 4.2K current density \( J_c \) (in A/mm\(^2\)) and magnetic field (in T) for LHC High Luminosity and FCC. The FCC Target is 1500 A/mm\(^2\) at 16 T.
Application Needs vs Material Optimization

**Application requirements**
- High in-field $J_c$
- High RRR (>100)

**Material optimization**
- Improved/optimized pinning
- Maximized rel. A15 content
- Optimized and homogeneous A15 composition
- Homogeneous grain morphology and small grain sizes
- Integrity of (Nb) barrier

**Heat Treatment**
Delicate balance of conflicting requirements
Fully optimized Nb$_3$Sn conductor?

PIT 192 – Nb7.5 wt% Ta

Residual core (~ 22 %)

Large grains (~ 25 %)

Small grains

RRP 54/61 – Nb7.5 wt% Ta


A. Ballarino, CERN
Pinning: Nb-Ti vs Nb₃Sn

**NbTi: α-precipitates**

**Nb₃Sn: grain boundaries**

**Dominant pinning mechanism:**

grain boundaries (vortex pinning)

Diameter of Nb₃Sn grains = 100-200 nm

Meingast, Lee and DCL, J. Appl. Phys. 66, 5971

Pinning: Nb-Ti vs Nb$_3$Sn

The graph shows the normalized pinning force ($F_p/F_{p\text{max}}$) as a function of the reduced field ($B/B_{c2}$) for two different materials: Nb$_3$Sn and Nb47\%Ti. The graph indicates that Nb$_3$Sn has a higher pinning force compared to Nb47\%Ti, with a peak at approximately 100-200 nm grains. The reduced field is normalized to $B\sim 5$ T.
Nb$_3$Sn for higher fields

- Increase pinning force and efficiency

$J_c \propto \frac{\text{GBD}}{d}$

$\text{d} = \text{grain diameter}$

GBD = Grain boundaries Density
Grain size at optimized heat treatments (150-200 nm) vs vortex spacing at operational fields (~12 nm at 16 T). Needed matching of spacing of pinning sites to vortex spacing.

Grain refinement possible by lowering the reaction temperature. But this is in conflict with the need of reaching stoichiometric Sn composition in the A15 phase → delicate interplay between A15 gain boundary density and compositional homogeneity.
Introduction of a **nano-inclusions** in the Nb$_3$Sn $\rightarrow$ increase of the pinning strength by:

- **Reduction of grain size** (pinning by grain boundary)
- **Enhanced point pinning** induced by additional defects

**Periodicity of lattice broken** at the grain boundaries and/or at the interface with an inclusion/precipitation
Nb₃Sn – Grain size refinement via AP

Thin films produced by electron beam co-evaporation

Grain size refined to 15-20 nm

(Fp)max shifted to ~ 0.5 Birr


Sc doping

D. Dietrich and A. Ballarino, CERN
Nb$_3$Sn – Grain size refinement via AP (Nb-Zr)$_3$Sn wires produced by Internal Oxidation method

- ZrO$_2$ precipitates in Nb$_3$Sn wires


![Graph showing normalized pinning force vs. reduced field](image)

- Artificial pinning via oxide nano-inclusions

12/04/2016
Nb$_3$Sn –AP via Ta nanoinclusions

Bronze-route processed wires


Artificial pinning via metallic nano-inclusions

12/04/2016
Nb$_3$Sn – AP via irradiation

Radiation induced nano-site defect clusters acting as pinning enters → enhancement of $J_c$

$F'_p = k(\alpha f'^G.B + \beta f'^P.P)$

GB Pinning
Point Pinning

Neutron irradiation at ATI

T. Spina, C. Scheuerlein, D. Richter, B. Bordini, L. Bottura, A. Ballarino, and R. Flükiger
- **Nb$_3$Sn** has **potentials for higher Jc** at 16 T

- **AP** can enable achievement of the **target Jc performance** with the required margin required for assuring a large-scale and cost-effective production
**Nb₃Sn Conductor for FCC - Quantity**

<table>
<thead>
<tr>
<th>LHC</th>
<th>FCC-hh (baseline)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 km, 8.33 T</td>
<td>100 km, 16 T</td>
</tr>
<tr>
<td>14 TeV (c.o.m.)</td>
<td>100 TeV (c.o.m.)</td>
</tr>
<tr>
<td>1200 tons Nb-Ti</td>
<td>6000 tons Nb₃Sn</td>
</tr>
<tr>
<td>200 kg HTS</td>
<td>3000 tons Nb-Ti</td>
</tr>
</tbody>
</table>
FCC Nb$_3$Sn conductor – Series production

- Total quantity of conductor – estimated on the basis of the present input from magnet design
  ~ 6000 tons

- Required a total production world-wide of ~ 700 - 800 tons/year over a period of ~ 7 years (if production by 8 companies)

- **ITER** production: world-wide production of up to 100 tons/year (8 companies)

- Need for **industrial scaling-up** of facilities
FCC Nb₃Sn conductor - Cost

- **Target cost**: $< 5 \text{ Euro/kA m} (16 \text{ T}, 4.2 \text{ K})$

- Cost of **state-of-the-art accelerator-type Nb₃Sn conductor** (estimate based on procurement of relatively small – $\sim 1$ ton – quantities of material):
  - $\geq 10 \text{ Euro/kA m} (12 \text{ T}, 4.2 \text{ K}) \rightarrow$
  - $> 20 \text{ Euro/kA m} (16 \text{ T}, 4.2 \text{ K})$

- **Increase of Jc @ 16 T** (from 1000 A/mm² to 1500 A/mm²): most effective way of decreasing cost. Importance of choice of technology, that should enable scale-up, and wire layout/composition

- Analysis and improvement of **both processing and manufacturing costs** (for raw materials and wire) required

12/04/2016 A. Ballarino, CERN
## Conductor development strategy

### Intermediate goals (4 years program)

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<tr>
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<td>km</td>
<td>≥ 5</td>
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</table>

*Je ~ 600 A/mm²

*Cu: non Cu ~ 1

** 16 T, 4.2 K

Scalability and potentials for large production
Conductor development program for FCC

- Conductor development program being launched by CERN:
  - Four years activity (2016-2019);
  - Focus is on demonstration of current capability at 16 T (Jc);
  - Production of wire in industry world-wide
  - Contribution of external institutes for material characterization and study
  - Production at CERN of Rutherford cables and possibly assembly and test of short model coils

A. Ballarino, CERN 12/04/2016
Collaborations launched on Nb₃Sn development for FCC

- **CERN/KEK** – Japanese contribution. Japanese industry (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku University and NIMS). **Kick-off meeting** at KEK in February 2016

- **CERN/Bochvar High-technology Research Inst.** – Russian contribution. Russian industry (TVEL) and laboratories

- Collaboration agreement with the **Technical University of Vienna (TUW)**

- Collaboration agreement with the **Applied Superconductivity Centre** at Florida State University
Collaborations to be launched

$\text{Nb}_3\text{Sn}$ - Development for FCC

- CERN/KAT – Korean industrial contribution
- CERN/Bruker – European industrial contribution

Technologies being analysed by industry:

- Internal Tin Distributed Barrier
- Internal Tin Single Barrier
- Powder In Tube
CERN /KEK Collaboration Agreement

**Task 1:** Definition of the **manufacturing route(s) and technologies**

**Task 2:** Definition of the **billet(s) and wire(s) layout and composition**

**Task 3:** Fabrication of **R&D billets**

**Task 4:** **Characterization** of wire produced from R&D billets

**Task 5:** Fabrication of **HFM wire (~ 20 km)** that will be **cabled at CERN** and used at CERN for construction of prototype **short-model coils**

Afternoon talk by T. Ogitsu
LHC
27 km, 8.33 T
14 TeV (c.o.m.)
1200 tons Nb-Ti
200 kg HTS

FCC-hh
100 km, 16 T
100 TeV (c.o.m.)
6000 tons Nb$_3$Sn
3000 tons Nb-Ti

FCC-hh
80 km, 20 T
100 TeV (c.o.m.)
9000 tons LTS
2000 tons HTS

HTS for FCC ?
BSCCO 2212

D. Larbalestier et al., Nat. Mat. 13, 375–381 (2014)

BSCCO 2212
100 bar OP

BSCCO 2212
1 bar

Isotropic material

D. Dietderich et al., LBNL

12/04/2016
A. Ballarino, CERN
# REBCO – Industrial Production

<table>
<thead>
<tr>
<th>REBCO layer</th>
<th>PLD</th>
<th>MOD</th>
<th>MOCVD</th>
<th>RCE</th>
<th>CSD</th>
<th>IBAD ABAD</th>
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A. Ballarino, CERN

12/04/2016
Slide courtesy of T. Puig

Production Capacity: 1000 Km/yr
Piece length: 500 m
REBCO – Nanocomposite materials

- **Nanoengineering of the defect structure** in the REBCO film

- **Optimization** of performance at the operating temperature and field:
  - $J_c(T, B)$
  - $J_c(T, B, \theta)$

Nanoscale defects for isotropic and strong flux pinning
Average BZO size 5.5 nm
Average spacing ~ 12 nm
Density = $6.9 \times 10^{11}$ cm$^{-2}$!

BZO size mostly 3 nm
Spacing 12 nm

Typical size of BZO in high lift factor tapes made in conventional MOCVD system: 5 – 6 nm

Courtesy of V. Selvamanickam
REBCO Tape for High Fields

Pinning Force (GN/m³) vs. Field (T)

- REBCO, Houston, 15%Zr
- REBCO, Fujikura
- REBCO Bruker
- REBCO SuperOx
- Nb3Sn

65 GN/m³

4.2 K

Courtesy of T. Puig, adapted

12/04/2016
REBCO Tape for High Fields

![Graph showing REBCO tape performance under high magnetic fields.](image)

- **Je~1500 A/mm²**
- **Je~500 A/mm²**
- **Je~400 A/mm²**

16 T

Magnetic Field (T)

**courtesy of V. Selvamanickam and T. Puig, adapted**
REBCO Cables in Magnets

~1000 m REBCO tape
~70 m of cable

Aperture = 40 mm

5 T in a background field of 15 T

J. Van Nugteren and G. Kirby, CERN, Eucard 2

HTS use in magnets requires major re-thinking of existing technology and mode of operation – and prototype coils are needed
Conclusions

- **Performance** requirements for Nb$_3$Sn conductor are challenging

- A **large industrial effort** is needed in order to convince the community on performance and feasibility of a potential (very) large scale production

- **Synergy** between magnet designers, superconductor experts, material scientists and industry is required. This synergy is fostered via R&D Collaborations with both industrial partners and external laboratories

**FCC Conductor development starts now !**
Thanks for your attention!
MgB$_2$ for High Fields?

- Simple binary composition
- No weak links at grain boundary
- Low electro-magnetic anisotropy
- Produced with known PIT technology as round wire
- Potentially cheap

But

- Poor connectivity (porosity, second phases at grain boundaries)
- Required improvement of in-field performance
Doping with C source (nano-C, SiC, C nanotubes, B₄C,...) – to date C is the only element confirmed to be able to enhance Bc₂. C substitutes B → increase ρ_N and pinning strength (fine grains → GB density)

No effect of nano-particles additions

MgB\textsubscript{2} for High Fields?

- MgB\textsubscript{2} roadmap for in field improvement in place
- Wire performance is expected to reach useful level at 10+Tesla in the next four years
- Activities are focusing on boron optimization, improved mechanical processing and wire architecture

---

**Boron**
Boron of higher quality than presently used (99\% and + compared to 95-98\% of today) is known to allow for 50-100\% performance improvement.

**Particle size control**
Control of particle size is fundamental to achieve high MgB\textsubscript{2} density, and increase in-field performance through grain boundary pinning.

**MgB\textsubscript{2} doping**
Optimal Carbon doping concentration (3-8\%) and vehicles for it will be introduced in production wires without segregation at grain boundaries.

**Connectivity**
Higher MgB\textsubscript{2} density in final wire, and more clean MgB\textsubscript{2} powders thanks to the handling and treatment in controlled atmosphere will increase connectivity further.

**Superconductor filling factor**
Increase in filling factor to > 40\% will be allowed by optimized cold working processes.

---

![Diagram](image.png)

**Columbus Superconductors**

*Courtesy of G. Grasso*

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<table>
<thead>
<tr>
<th>Year</th>
<th>-&gt; 2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
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<tbody>
<tr>
<td>MRI</td>
<td>Dedicated &amp; low field MRI</td>
<td>1,5 Tesla</td>
<td>1,5 Tesla &amp; 3 Tesla dedicated</td>
<td>3 Tesla total body</td>
<td>7 Tesla total body</td>
<td>9 Tesla +</td>
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<tr>
<td>Field</td>
<td>2-3 Tesla</td>
<td>4-5 Tesla</td>
<td>6 Tesla</td>
<td>7 Tesla</td>
<td>8-9 Tesla</td>
<td>10 Tesla +</td>
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