Industrial Manufacturing of Low Temperature Superconducting (LTS) wires

Mikael Holm     Luvata Pori Oy

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OUTLINE OF THE PRESENTATION

• Introduction to Luvata and Luvata Pori Superconductors

• Low Temperature Superconductors Industrially manufactured (technical superconductors)
  • NbTi
  • Nb3Sn

• Present and future applications

• Film of Manufacturing (about 10 min)

• Filament count brainstorming
Some Facts about Luvata

• Over 7,000 employees
• 35 production facilities in 18 countries
• 65 companies
• Total sales of EUR 1.5 billion 2009
• Deliveries of 231 Ktonnes
• Diverse and visionary board and owners
• Significant position in every market we have entered
Some Facts about Luvata

- Organised to 4 divisions

<table>
<thead>
<tr>
<th>Special Products</th>
<th>ACR Tubes</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Welding Electrodes</td>
<td>- ACR tubes</td>
</tr>
<tr>
<td>- Superconducting wire</td>
<td>- Hairpins</td>
</tr>
<tr>
<td>- Photovoltaic wire</td>
<td>- Computer cooling</td>
</tr>
<tr>
<td>- Electrical material</td>
<td>- Tubes for radio frequency cables</td>
</tr>
<tr>
<td>- Metallurgical applications</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rolled Products</th>
<th>Heat Transfer Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Connector material</td>
<td>- Indoor climate solutions</td>
</tr>
<tr>
<td>- Telecom material</td>
<td>- Mobile climate solutions</td>
</tr>
<tr>
<td>- Industrial material</td>
<td>- Food storage and transport-refrigeration solutions</td>
</tr>
<tr>
<td>- Architectural products</td>
<td>- Industrial process solutions</td>
</tr>
<tr>
<td>- Solar thermal</td>
<td></td>
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<tr>
<td>- Automotive HX material</td>
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</table>
Local support from a globally successful company

<table>
<thead>
<tr>
<th>Americas</th>
<th>Europe</th>
<th>Asia</th>
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<tbody>
<tr>
<td>Delaware OH</td>
<td>Austria</td>
<td>China (7)</td>
</tr>
<tr>
<td>Buffalo NY</td>
<td>Finland (2)</td>
<td>Malaysia (2)</td>
</tr>
<tr>
<td>Waterbury CT</td>
<td>Italy (7)</td>
<td>Thailand (2)</td>
</tr>
<tr>
<td>Appleton WI</td>
<td>Netherlands (2)</td>
<td></td>
</tr>
<tr>
<td>Franklin KY</td>
<td>Spain (2)</td>
<td></td>
</tr>
<tr>
<td>Grenada MS</td>
<td>Sweden (3)</td>
<td>Korea</td>
</tr>
<tr>
<td>Jacksonville TX</td>
<td>UK (8)</td>
<td>Singapore</td>
</tr>
<tr>
<td>Temecula CA</td>
<td></td>
<td>Vietnam</td>
</tr>
<tr>
<td>Tampa FL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Juarez, Mexico</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Memphis TN</td>
<td>France</td>
<td></td>
</tr>
<tr>
<td>Chicago IL</td>
<td>Germany</td>
<td></td>
</tr>
<tr>
<td>New Hudson MI</td>
<td>Poland</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Russia</td>
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</tbody>
</table>
We operate in a wide range of industries

ARCHITECTURE & BUILDING
AUTOMOTIVE
CONSUMER PRODUCTS
ELECTRICAL
ELECTRONICS

HVAC&R
MEDICAL
METAL & METALLURGICAL
OIL & GAS
POWER GEN. & DISTRIBUTION

PROCESS
SUPER-CONDUCTORS
SUSTAINABLE ENERGY
TELECOM & COMMUNICATION
WELDING
LUVATA PORI SUPERCONDUCTORS

- Electronic Applications (Target production line)

- Copper and steel components (Machine Shop)

- Superconductors

42  54  Nb3Sn IT 6500  WIC  54
Low Temperature Superconductors (LTS)
Low Temperature Superconductors (LTS)

A superconducting material with a critical temperature (Tc) below 23.2K is known as a Low Temperature Superconductor (LTS)

A superconducting material with a critical temperature above 23.2K is known as a High Temperature Superconductor (HTS)
The superconducting region is determined by:

- critical current density \([J_c]\)
- critical temperature \([T_c]\)
- critical magnetic field \([H_c]\)

Superconductors are in superconductive state only when in superconducting region.

If any of these critical parameters is exceeded, transfer from superconducting state to normal state begins.
Properties needed from superconductors that can be used in industrial manufacturing

- Long unit lengths
- Good workability properties
- Uniform quality (Ic/Jc)
- Competitive manufacturing cost
- Good mechanical properties for magnet winding/cabling
- Copper as stabilized matrix material; high electrical/thermal conductivity, good mechanical strength, good ductility
- Can be apply robust insulation (enamelling, braiding)
- Adequate critical temperature, magnetic field and current
- Flexible design (filament size/number, SC-ratio, diameter..)

Technical superconductors

- NbTi
- Nb3Sn

13 | Luvata Pori Oy Superconductors
Copper as Matrix Material - Stability

• Properties needed of a good matrix material
  • High electrical and thermal conductivity
  • High heat capacity
  • Good mechanical strength at cryogenic temperature
  • Good adherence to the superconductor
  • Good ductility for forming and winding

• Residual Resistance Ratio = RRR
  • The resistance at room temperature and at 4.2 K (-269 °C) is measured
  • $RRR = R(20 \, ^\circ C)/R(-269 \, ^\circ C)$
  • $R(20 \, ^\circ C)$ very constant
  • $R(-269 \, ^\circ C)$ depends on the purity level

• OF: $RRR = 50 - 200$
• OFE: $RRR = 200 – 250$
• OFC: $RRR = 400 – 1000$
Production flow for technical superconductors

**TECHNICAL SUPERCONDUCTOR STRAND**

- Insulated
- Bare or coated

**MAGNET MANUFACTURING**

**CABLE/CONDUCTOR MANUFACTURING**

**MAGNET MANUFACTURING**

**SYSTEM ASSEMBLY**

MRI, NMR

**SYSTEM ASSEMBLY**

LHC, FUSION
The general design of NbTi

Luvata OK 55 for NMR
The general design of Nb3Sn (Bronze)

Luvata OKSn 11600
The general design of Nb3Sn (Internal Tin)

Luvata Fusion type

Copper stabilizer
Ta-diffusion barrier
Sn-source
Nb-filament area
Nb3Sn formation

Before

Cu-Sn

Nb

reaction heat treatment
700°C 80 hours

Tin diffuses
to Nb filament
and react Nb3Sn

After

Nb3Sn

Nb3Sn superconductive material is brittle → wind and react
# Properties NbTi vs. Nb3Sn

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
<th>Nb47% Ti</th>
<th>Nb3Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tc at 0T</td>
<td>K</td>
<td>10</td>
<td>18.3</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>T(max)</td>
<td>11</td>
<td>25</td>
</tr>
<tr>
<td>Critical current density</td>
<td>A/mm²</td>
<td>3300 (5T), 400 (9.5T)</td>
<td>12000 (5T), 3000 (12T)</td>
</tr>
<tr>
<td>Structure</td>
<td></td>
<td>Solid solution alloy</td>
<td>Intermetallic compound</td>
</tr>
<tr>
<td>Ductility</td>
<td></td>
<td>Ductile/tough</td>
<td>Ductile, brittle (after reaction)</td>
</tr>
<tr>
<td>Manufacturing methods</td>
<td></td>
<td>Co-process, hot/cold</td>
<td>Internal-Tin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Precipitation HT</td>
<td>Bronze</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Power-In-Tube</td>
<td></td>
</tr>
<tr>
<td>Max unit length</td>
<td>km</td>
<td>50 - 270</td>
<td>10 - 40</td>
</tr>
<tr>
<td>Max unit weight</td>
<td>kg</td>
<td>200-450</td>
<td>50-100</td>
</tr>
<tr>
<td>typical final diameter</td>
<td>mm</td>
<td>0.4 - 2.0</td>
<td>0.6 - 1.5</td>
</tr>
<tr>
<td>Cu/Sc-ratio</td>
<td></td>
<td>1-14</td>
<td>0.3 - 1.5</td>
</tr>
<tr>
<td>Filament size</td>
<td>micrometer</td>
<td>2.5 - 120</td>
<td>2 - 6</td>
</tr>
<tr>
<td>Filament number</td>
<td></td>
<td>1-40 000</td>
<td>3000 - 40 000</td>
</tr>
<tr>
<td>Price</td>
<td>EUR/kg</td>
<td>50-200</td>
<td>500 - 1000</td>
</tr>
<tr>
<td>Technical price</td>
<td>EUR/kAm</td>
<td>1-4</td>
<td>10-20</td>
</tr>
</tbody>
</table>
 NbTi Manufacturing Process

Two Phase

"Mono process" (3 … 6 weeks)
"Multi process" (6 … 18 weeks)
NbTi Manufacturing Process
Phase I of Manufacture: Mono

Cleaning of Components

Billet Assembly

Vacuum & EB-Welding

Isostatic Pressing

Hot Extrusion

Drawing on big Bench

Cutting of Mono Sticks for the Multi Assembly

Typical Mono Cross Sections
“MONO” Rods: 25mm – 2.5mm
Phase II of Manufacture: Multi

1. Cleaning of Components
2. Billet Assembly
3. Vacuum & EB-Welding
4. Hot Extrusion
5. Drawing on big Bench
6. Drawing on Bull Block
7. Heat Treatment
8. Serie drawing
9. Twisting
10. Final (Over) draw and Inspection

Testing:
- dimensions
- current values
- Cu/Sc
- RRR
- tensile strain
LTS Present Applications
Magnetic Resonance Imaging (MRI) is the largest commercial application of superconductivity. MRI is a powerful medical diagnostic tool.

- > 50% LTS market
- over 2500 units annually
- 5% annual growth
- 60% share of 1.5T and 25% share of 3T devices
Magnetic Resonance Imaging (MRI)

The 1.0 T high-field open (HFO) scanner Panorama from Philips

Philips Mobile MRI

Philips Cylindar MRI
Magnetic Resonance Imaging

Ankle

Prostate (7.0T)

entire spine
Nuclear Magnetic Resonance (NMR)

NMR is considered the most versatile spectroscopic tool in science today.

One of the most important techniques in modern science as in physics, chemistry, materials science, biology and medicine.

10% of LTS market
Nuclear Magnetic Resonance (NMR)

Nuclear magnetic resonance (NMR) is based upon the measurement of absorption of radiofrequency (RF) radiation by a nucleus in a strong magnetic field. Absorption of the radiation causes the nuclear spin to realign or flip in the higher-energy direction. After absorbing energy the nuclei will re-emit RF radiation and return to the lower-energy state.
High Energy Physics (LHC)

The Large Hadron Collider (LHC) located near Geneva, Switzerland. It is the largest and most powerful particle accelerator in the world with a circumference of 27 kilometers.

The rings of particle accelerators are made of superconducting magnets total amount is 1,500 tons of superconducting cable.
High Energy Physics (LHC)

View of Cern LHC tunnel 100 meters below the earth’s surface showing superconducting magnets inside the tubes.
High Energy Physics (LHC)

Luvata OK 6400
Strand diameter 0.823mm
Filament number 6400
Filament size 6 microns

SEM picture of etched finefilamentary superconducting wire. Filament size about 5 microns and spacing between filaments about 1 micron.

- Number of strands: 36
- Cable width: 15.10 mm
- Cable mid thickness: 1.48 mm
- Keystone angle: 0.9 degrees
- Transposition pitch: 105 mm
- Critical current, @1.9K and 9T: >12960 A
- Cable Unit Length: 750 m
High Energy Physics (CMS)

The Compact Myon Solenoid (CMS) is one of two large general-purpose particle physics detectors on LHC
High Energy Physics (CMS)

Luvata OK 552

- 552 Filaments
- Filament Dia 38 μm
- Strand Dia 1.280 mm
- Cu/Sc Ratio 1.1 : 1
- Note the Identification code in the core
- Typical continuous piece length
  >13.75 km (=5u1’s)
- Ic @4.2K & 5T: >2000A

CMS Gold Award & Crystal Award winner
Superconducting Magnetic Energy Storage (SMES)

Currently used for short duration energy storage to improve power quality. Power is available almost instantaneously.

For example manufacturing plants requiring ultra stability power, such as microchip fabrication facilities and paper mills.

Luvata OK 3900
CuMn-resistivity matrix
Strand suitable for AC-applications
INTERNATIONAL THERMONUCLEAR EXPERIMENT REACTOR ITER

• To be build in France, Cadarache (2008 – 2016)

• ITER Partners:
  • CN, EU, IN, JA, KO, RF ja US

Magnets:
  • 48 together
  • NbTi 240 t and Nb3Sn 520 t

• Luvata Partners:
  • EU – ITER (1993 =>)
Alpha Magnetic Spectrometer II (AMS II)

- AMS II is going to be taken to the "International Space Station" (ISS)
- Measuring time is estimated to be between 3 – 5 years
- Will search for antimatter and dark matter
- Estimated start up time 2011
**OTHER APPLICATIONS**

Crystal Grover (NbTi)
Relative large silicon bars

Maglev train (NbTi)
High speed technology up to 550 km/h

Magnetic Separation (kaolin clay processing)
up to 5T (NbTi), copper separators max 1.8T
+productivity, reduction of overall energy consumption
LTS Future Applications
Magnetic Resonance Imaging (MRI)

Up to higher fields

3T standard soon (clinical use)

7T or even up to 11.7T (limit for NbTi, operating temperature 1.8K), research use

+ better resolution, sensitivity

+ new areas as in-situ/in vivo etc..

+ decreased measuring time
Magnetic Resonance Imaging (MRI)

CEA Saclay project

Neuroscience research centre in France

Full body 11.7 T MRI-magnet
Largest MRI systems ever built.

The project will finish by end of 2011

70 tons of CiC (cable in channel)

All SC-material will be manufactured by Luvata Waterbury.

irfu.cea.fr/Images
Proton Therapy

Proton therapy is widely regarded as the optimal radiation treatment for a wide variety of cancers because of its significant clinical advantages compared to conventional high energy X-rays.

The advantage of proton therapy is the ability to precisely localize the radiation dosage.

SC- application need high Jc Nb3Sn (IT) strand

Room-sized proton accelerators to bring the treatment to existing medical centers.
Nuclear Magnetic Resonance (NMR)

Up to higher fields  1 GHz (23,4T) Nb3Sn

Hybrid magnet technology up to 45 T

Combination of resistive and SC-magnet. Peak field is not limited by the critical field of a superconductor

+ better resolution, sensitivity
+ new research areas

Cryogen free SC-magnet  (Nb3Sn)

Small research magnets
Upgrade of HEP device

LHC
Replace existing NbTi-dipole magnets to high-field (~ 15 T) ones (Nb3Sn IT)

JT60SA
Fusion tokamak reactor
Demo reactor for ITER
Replace magnet system (TF/CS/EF/CC-coils) using Nb3Sn and NbTi conductors
High Energy Physics (FAIR)

GSI is planning to build the new accelerator center FAIR (Facility for Antiproton and Ion Research) in Germany. One of the important elements is SIS-300 synchrotron will use fast-cycled superconducting dipoles operated at 1 T/s.
High Energy Physics (FAIR)

The magnet cross section
High Energy Physics (FAIR)

The facility **FAIR** including the synchrotrons

SIS100 and SIS300
## Global Market for Superconductivity (in M€)
Conectus, December 2009

<table>
<thead>
<tr>
<th>Business Field</th>
<th>2007</th>
<th>2009</th>
<th>2011</th>
<th>2013</th>
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</thead>
<tbody>
<tr>
<td>Research and Technical Development (RTD)</td>
<td>660</td>
<td>765</td>
<td>845</td>
<td>955</td>
</tr>
<tr>
<td>Magnetic Resonance Imaging (MRI)</td>
<td>3300</td>
<td>3355</td>
<td>3435</td>
<td>3525</td>
</tr>
<tr>
<td><strong>TOTAL OF RTD &amp; MRI</strong></td>
<td>3960</td>
<td>4120</td>
<td>4280</td>
<td>4480</td>
</tr>
<tr>
<td>New Large Scale Applications</td>
<td>65</td>
<td>100</td>
<td>155</td>
<td>325</td>
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<tr>
<td>New Electronics Applications</td>
<td>60</td>
<td>80</td>
<td>125</td>
<td>180</td>
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<tr>
<td><strong>TOTAL OF EMERGING NEW BUSINESSES</strong></td>
<td>125</td>
<td>180</td>
<td>280</td>
<td>505</td>
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<tr>
<td><strong>TOTAL MARKET</strong></td>
<td>4085</td>
<td>4300</td>
<td>4560</td>
<td>4985</td>
</tr>
<tr>
<td>Market Shares of LTS</td>
<td>4025</td>
<td>4205</td>
<td>4385</td>
<td>4600</td>
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<tr>
<td>Market Shares of HTS</td>
<td>60</td>
<td>95</td>
<td>175</td>
<td>385</td>
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THANK YOU FOR ATTENTION!