Status of Superconducting Materials and Applications in China

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Northwest for Nonferrous Metal Research (NIN)

Western Superconducting Technologies Co., Ltd. (WST)

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Outline

1. Overview of R&D programs for superconductivity in China
2. Progress of low Tc superconductors (LTS)
3. Progress of high Tc superconductors (HTS)
4. Progress of superconducting applications
   Magnet application /Electrical power application
5. Summary
1. Overview of R&D programs for superconductivity in China

A. National High Technology Research and Development Program (863 Program)
B. National Basic Research Program of China (973 Program)
C. National Fusion Research Program of China (ITER China)
D. National Natural Science Foundation of China (NSFC)
The R&D Programs for Superconductivity in China

1. National High Technology Research and Development Program (863 Program)

Main goals:
- Manufacture technology of Superconducting materials for practical applications.
- Superconducting technology: cable, FCL, magnet, and filter.

Main Projects including:
- Manufacture techniques of high-performance Coated Conductor superconducting tapes
- Manufacture techniques of superconducting strands for high-performance MRI application
- Nb3Sn superconducting wires for high-field application
- Large capability HTS Superconducting cables
- High voltage level superconducting FCL

Principal Investigator: Prof. Pingxiang Zhang

Total fund: 200 Million RMB (FY2011-FY2015) to 32 groups with more than 300 researchers.
The R&D Programs for Superconductivity in China

2. National Basic Research Program of China (973 Program)

Main goals:
- Exploring the novel superconducting mechanisms and superconductors.
- Basic scientific questions of superconducting materials in application.

Main Projects including:
-- Exploration and structure characterization of novel superconductors
-- Study on unconventional superconducting materials and mechanism questions
-- Theory and calculation of HTS
-- Novel HTS films and their interface characters
-- Basic research of micro/nano scale superconducting materials and devices

Principal Investigator: Prof. Haihu Wen

Total fund: 100 Million RMB (FY2011-FY2015) to 14 groups with more than 200 researchers.
The R&D Programs for Superconductivity in China

3. National Fusion Research Program of China (ITER China)

Main goals:
- Developing new high-performance superconducting materials for high-field magnet application in next-generation fusion reactor.

Main Projects including:
- R&D of High-performance Nb$_3$Al superconducting long wires for 15 T magnet
- R&D of High-performance Bi-2212 round stands for 20 T insert magnet
- Development of high-strength and high-J$_c$ Bronze Nb$_3$Sn strands
- Novel insulation and anti-irradiation materials for high-field magnet application
- Design of China Fusion Engineering Test Reactor

Total fund: 150 Million RMB (FY2011-FY2015) to 10 groups with more than 100 researchers.
The R&D Programs for Superconductivity in China

4. National Natural Science Foundation of China (NSFC)

Main goals:
- Free exploration for basic research on superconducting materials and application.
- Training the scientific talents.

Main Projects including:
- Novel theory and superconductor exploration
- New synthesis methods and mechanisms on superconducting materials
- New theory and methods on superconducting electrical power application
- New application possibility on medical equipment, scientific instrument and transportation
- Interdiscipline researching of superconducting technologies with microscopy, mechanics, life sciences and materials sciences;
- Funding for the foreign young researchers to work in China

Total fund: 150 Million RMB (FY2011-FY2015) to 200 groups with more than 1000 researchers.
Progress of SC and its application in China (2011-2015)

Materials

YBCO CC: 50m, Ic=140A@77K
Laboratory scale

YBCO CC: 1000m, Ic=280A@77K
Industry scale

LTS:
Starting mass production

180t NbTi and 30t Nb_3Sn strands for ITER, 100t
strands for MRI and HEP application

2011 2012 2013 2014 2015

Application

Power DEMO: HTS Power Substation

Cable: 380m, 10000A DC

FCL: 220kV, 3 Phase

FCL: 550kV, 3 Phase

The R&D of superconducting materials and applications in China cover
all the fields today.
2. Progress of LTS (NbTi/Nb$_3$Sn/Nb$_3$Al)

A. NbTi alloy and strands
   Iter and MRI

B. Nb$_3$Sn strands
   Internal Sn and Bronze methods

C. Nb$_3$Al wires
   PIT and Jelly-roll methods

- Western Superconducting Technologies Co., Ltd. (WST)
- Northwest Institute for Nonferrous Metal Research (NIN)
Overview of NbTi and Nb₃Sn Strands for ITER

WST launched mass production of NbTi and Nb₃Sn strands for ITER in 2009 and delivered 180t NbTi and 30t Nb₃Sn strands until 2015.

WST Stock No. 831628, NEEQ China

ITER project pushed the R&D and production of LTS in China
The distribution of energy in the Nb element in electrode is the key issue for homogeneity.

High homogeneity of component and microstructure

High-homogeneity NbTi alloy has been developed and produced in large scale for ITER and MRI application.
Fabrication of large size NbTi/Cu composite billet

WST developed the fabrication technology to make large size NbTi/Cu billet with high quality long wires.
Bundledrawing: Ultrafine filamentary NbTi strands

- Cross section of NbTi after extrusion
  - One step extrusion
  - 65 cold drawing process
  - 99.99% deformation ratio

- 0.73mm final strand

- Distribution of filaments
  - Transverse
  - Longitudinal

- Surface of filaments with diameter of 8 µm

- Subelements
  - NbTi
  - Cu
  - Nb

The maximum unit length of final NbTi strand for ITER with ultrafine filament is **90km**
Enhancement of performance of NbTi by optimization of HT and additional deformation

The 4 times HT method was developed instead of traditional 6 times HT method.

The Heat treatment times and additional deformation have significant effect microstructure of NbTi to enhance the critical current density of strands.
**NbTi Strand for MRI Application**

- Monolith and WIC wire for MRI and scientific application have been developed and manufactured in large scale.

**The domestic MRI system manufacturers in China**

- www.united-imaging.com
- http://alltechmed.com
- http://www.xmc.cn

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**Graph:**

- The performance of different NbTi wires meet the requirements of MRI.
Internal-tin Nb$_3$Sn Strand: Conductor design

**Key issues**

- High $J_c$
- Low AC loss
- High content of Nb$_3$Sn phase
- High ratio of Nb and Sn
- Distance of filaments
- High ratio of Cu

**Ratio of Cu:Nb:Sn = 2.97:1.57:1**

Filaments Number of Nb$_3$Sn strand is 3040.

The subelement in strand

- Low AC loss: (To avoid coupling)
  - The copper surround Nb filament
  - The copper surround subelement

The distance of filaments is about 2 $\mu$m and of subelements is about 5 $\mu$m

The ratio of Cu/Nb/Sn elements and distance ensure high $J_c$ and low AC loss of internal-tin Nb$_3$Sn strands for ITER
Internal-tin Nb$_3$Sn Strand: Fabrication

<table>
<thead>
<tr>
<th>Step</th>
<th>characteristic</th>
<th>Size (mm)</th>
<th>Drawing rate (%)</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low Drawing rate</td>
<td>65-47</td>
<td>7-14</td>
<td>Hardening of all elements synchronously</td>
</tr>
<tr>
<td>2</td>
<td>High Drawing rate</td>
<td>47-5.85</td>
<td>23-29</td>
<td>Deformation of all elements synchronously</td>
</tr>
<tr>
<td>3</td>
<td>Middle Drawing rate</td>
<td>5.85-0.82</td>
<td>12-18</td>
<td>Low resistance to deformation</td>
</tr>
</tbody>
</table>

The special deformation controlling technology ensures the homogeneity of all elements in composite to get fine Nb$_3$Sn grains.
## Internal-tin Nb₃Sn Strand: New Structure

- New structure strand were fabricated and investigated to improve total performance for the future fusion application.

<table>
<thead>
<tr>
<th>Strand type</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cross section</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Structure feature</strong></td>
<td><strong>Cu split</strong></td>
<td><strong>Cu split</strong></td>
<td><strong>Cu split</strong></td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>Tin spacer</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>--</td>
<td>37 subelements</td>
</tr>
<tr>
<td><strong>Iₖ (A) @4.2K,12T</strong></td>
<td>&gt;250</td>
<td>&gt;280</td>
<td>&gt;270</td>
</tr>
<tr>
<td><strong>n value @4.2K,12T</strong></td>
<td>&gt;20</td>
<td>&gt;20</td>
<td>&gt;20</td>
</tr>
<tr>
<td><strong>RRR(273K/20K)</strong></td>
<td>&gt;100</td>
<td>&gt;100</td>
<td>&gt;100</td>
</tr>
<tr>
<td><strong>Qₕ (mJ/cm³) @4.2K,±3T</strong></td>
<td>&lt;300</td>
<td>&lt;340</td>
<td>&lt;320</td>
</tr>
</tbody>
</table>

*Qₕ level is efficiently decreased by Cu split in subelements. Iₖ is increased by tin spacers in final billets.*
Internal-tin Nb$_3$Sn Strand: Performance

- Heat treatment was investigated to understand the intrinsic property of the strand

**Duration at reaction temperature**

The increase rate of $Q_h$ is much more significant than $I_c$ when duration is varied from 55 h to 100 h.

**Temperature sensitivity**

$I_c$ is very sensitive to temperature fluctuation specially from 645 °C to 650 °C at field above 12 T.

Heat treatment duration has greater impact on $Q_h$

$I_c$ is very sensitive to temperature variation of ± 5 °C at high field
Bronze Nb$_3$Sn wires: Conductor design

Key issues to fabricate the Nb$_3$Sn wires with High Jc and low AC loss:

- a. High-Sn content in bronze
- b. Enough fine filament

Our design idea:

a) Using the high-Sn Bronze with 15.5 wt.% Sn content as the raw material;
b) Increasing the filament number to 13579, make the filament size up to 2 um;
c) Using the hetermophous bronze rod to make the filling ratio up to 97.8%.
Bronze Nb$_3$Sn wires: Conductor design

Effect of diffusion barrier on hysteresis loss

The SEM images of bronze processed Nb$_3$Sn strand after heat treatment
(a) Nb$_3$Sn strand with combined Nb-Ta diffusion barrier (Sample-1).
(b) Nb$_3$Sn strand with single Nb diffusion barrier (Sample-2).
(c) Nb$_3$Sn strand with single Ta diffusion barrier (Sample-3).

Performance of Nb$_3$Sn wires with different barrier design

<table>
<thead>
<tr>
<th></th>
<th>Sample -1</th>
<th>Sample -2</th>
<th>Sample -3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of filaments</td>
<td>13579</td>
<td>13579</td>
<td>11581</td>
</tr>
<tr>
<td>Filament material</td>
<td>Nb</td>
<td>Nb</td>
<td>NbTa</td>
</tr>
<tr>
<td>Barrier material</td>
<td>Nb+Ta</td>
<td>Nb</td>
<td>Ta</td>
</tr>
<tr>
<td>Ic (A) @4.2K, 12T</td>
<td>236</td>
<td>244</td>
<td>201</td>
</tr>
<tr>
<td>Hysteresis loss (mJ/cm$^3$) @4.2K, ±3T</td>
<td>159</td>
<td>309</td>
<td>53</td>
</tr>
</tbody>
</table>

- Nb$_3$Sn ring formed by Nb barrier leads a high loss.
- Ta strips interrupt the circular Nb$_3$Sn layer reacted by Nb barrier which results a middle loss.
Bronze Nb$_3$Sn wires: Performance

Effect of bronze/Nb ratio on $J_{cn}$

<table>
<thead>
<tr>
<th>Matrix material</th>
<th>Cu15.5Sn0.25Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filament material</td>
<td>Nb</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>13579</td>
</tr>
<tr>
<td>Bronze/Nb area ratio</td>
<td>2.5 2.2 2.0</td>
</tr>
<tr>
<td>Filament spacing(μm)</td>
<td>1.4 1.3 1.2</td>
</tr>
<tr>
<td>$I_c$ (A) @4.2K, 12T</td>
<td>236 239 244</td>
</tr>
<tr>
<td>$J_{cn}$ (A/mm$^2$)@4.2K,12T</td>
<td>907 923 930</td>
</tr>
<tr>
<td>$n$ value</td>
<td>37 36 40</td>
</tr>
</tbody>
</table>

- $J_{cn}$ increase slowly with the bronze/Nb area ratio reducing for the increase of Nb$_3$Sn volume fraction.
- By optimizing the design, now the $J_{cn}$ of bronze Nb$_3$Sn superconducting wires exceeds 900A/mm$^2$ at 4.2K and 12T.
Fabrication of Nb₃Al superconducting wire by combing ball-milling and PIT methods

By optimizing the fabrication technique, now the transport $J_c$ of Nb₃Al superconducting wires, made by PIT method, exceeds 100 A/mm² at 4.2K and 12T.
Development of Jelly-roll Nb₃Al superconducting wires

Superconducting properties of Nb₃Al wires by two heat-treatment routes:

(1) Low-temperature diffusion: Transport $J_c@4.2K \times 12T=670$ A/mm²;
(2) RHQ method: $T_c: 17.9$-$18.0$ K, $H_{c2}(0): 29.7$ T.
3. Progress of high Tc superconductors (HTS)

A. Bi2223 tapes and Bi2212 wires
B. MgB\textsubscript{2} wires
C. Fe-based wires
D. YBCO coated conductors
Bi2223 tapes and Bi2212 wires

- Western Superconducting Technologies Co., Ltd. (WST)
- Northwest Institute for Nonferrous Metal Research (NIN)
Bi-2223 HTS tapes

Bi-2223 tapes have been successfully used for extensive demonstration applications.

200-500 meters long Bi-2223 tapes can be fabricated in NIN in batches with the $I_c$ of $\sim 100\text{A}$, $J_c=4\times10^4\text{A/cm}^2$ (77K, s.f.).
Bi-2223 HTS tapes

NIN is now developing AgAu-sheath Bi-2223 tapes for the fabrication of current lead with low thermal conductivity for the design and build of CFETR in China.

Matrix: Ag-Au alloy (5.4 wt. % Au)
Thickness : 0.25 mm
Width : 4.3 mm
Critical Tensile Stress: 50 MPa
Critical Current : ~80 A

Our goal is to achieve AgAu-(Bi-2223) tapes with $I_c$ of ~120 A
Bi-2212 HTS wires

**Powder in tube process** is adopted in NIN for the fabrication of 200-m long Bi-2212 wires
Bi-2212 precursor powders fabrication

Modified Co-precipitation Process is adopted for the fabrication of Bi-2212 precursor powders with high uniformity and high reactivity.

2212 content: 97-98%
Residual carbon content: 150 ppm
Average Particle size: 3~6 µm
Cold working process for Bi-2212 wires

By improving the configuration design and optimize the cold working parameters, Bi-2212 wires with uniformly deformed filaments are achieved.

37×(18+1)
Partial melting process for Bi-2212 wires

Based on the study of phase evolution mechanism during partial melting process, we can control the growth of secondary phases and improve both the Bi-2212 phase content and the intergrain connections.

<table>
<thead>
<tr>
<th>Grey</th>
<th>Bi-2212</th>
</tr>
</thead>
<tbody>
<tr>
<td>White particles</td>
<td>Bi-2201</td>
</tr>
<tr>
<td>Black spherical particles</td>
<td>14:24 AEC</td>
</tr>
</tbody>
</table>
Development of Bi-2212 superconducting wires in NIN

Short samples:
- $I_c = 890$ A
- $J_{ce} = 1100$ A/mm$^2$
- $J_c = 5200$ A/mm$^2$
  (4.2 K, s.f.)

Batch production ability for 200-m long Φ1.0mm wires
- 4.2 K, 0 T: $J_{ce} \sim 920$ A/mm$^2$, $J_c \sim 4400$ A/mm$^2$.
- 4.2 K, 20 T: $J_{ce} \sim 270$ A/mm$^2$, $J_c \sim 1200$ A/mm$^2$.

Bi-2212 wires can achieve $J_c$ of $>1000$ A/mm$^2$ @4.2 K, 20 T, which shows great potential for the application in high-field magnets or large current cables.

(Oral: 3M-M-02.06)
# Trial-production of Bi-2212 CICC conductors

<table>
<thead>
<tr>
<th></th>
<th>First stage cable</th>
<th>Second stage cable</th>
<th>Third stage cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wire</td>
<td>2</td>
<td>2×3</td>
<td>2×3×7</td>
</tr>
<tr>
<td>Tension</td>
<td>20 N</td>
<td>20 N</td>
<td>30 N</td>
</tr>
<tr>
<td>Pitch</td>
<td>18-20 mm</td>
<td>49 mm</td>
<td>90 mm</td>
</tr>
</tbody>
</table>

- NIN is now working with IPP-CAS on the fabrication of Bi-2212 CICC;
- 42 Bi-2212 wires were adopted for 5m long conductor;
- $I_c$ measurement is on the way…
Overpressure treatment of Bi-based wires

Overpressure treatment is an effective method for the improvement of current capacity of Bi-based wires and tapes.

NIN is now developing the high-pressure treatment system, aiming at the further improvement of filament density and current capacity of Bi-2212 wires and Bi-2223 tapes.
MgB$_2$ wires

Northwest Institute for Nonferrous Metal Research (NIN)
Conductor design and optimization

Central reinforcement Materials

7-MgB$_2$ filaments

6-MgB$_2$ filaments +Cu reinforcement

6-MgB$_2$ filaments +Nb/Cu or NbTi reinforcement

Central filament broken
 Nb reinforced wire exhibits higher mechanical properties. The yield strength of the reinforced wire is about 118 MPa and only 50 MPa for the wires without reinforced. The Nb reinforcement could remarkably enhance the mechanical property of the 6 filaments MgB$_2$ wires.
Configuration design and optimization

Filament Number

<table>
<thead>
<tr>
<th>Filament</th>
<th>6</th>
<th>12</th>
<th>36</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgB₂</td>
<td>21.89</td>
<td>14.14</td>
<td>13.95</td>
</tr>
<tr>
<td>Nb</td>
<td>23.61</td>
<td>21.88</td>
<td>20.97</td>
</tr>
<tr>
<td>Cu</td>
<td>54.50</td>
<td>63.98</td>
<td>65.08</td>
</tr>
</tbody>
</table>

The intensity of 6 filaments wire is higher than that of other wires due to the higher Nb-content.
Fabrication of \textit{km}-grade MgB$_2$ wires

Production of \textbf{1500 m} MgB$_2$ wires/tapes

The preparation technology of kilometer MgB$_2$ wire is stable, we have prepared \textbf{20 kilometers} MgB$_2$ superconducting wires
Now we can produce 1500 meter MgB$_2$ superconducting wires. At 20 K, 2 T, $J_c = 4.3 \times 10^4$ A/cm$^2$
Fe-based wires

Institute of Electrical Engineering  Chinese Academy of Sciences
(IEE-CAS)
Is there still a room for the $J_c$ improvement by hot pressing?


**By Hot Pressing**

The high transport $J_c$ values were achieved in SrFe$_2$As$_2$/Ag tapes: $J_c \sim 1.0 \times 10^5$ A/cm$^2$ (4.2 K, 14 T)

At 4.2 K and 10 T:

$J_c = 1.2 \times 10^5$ A/cm$^2$

The superior $J_c$ can be attributed to higher grain texture and improved densification.

Practical level $J_c$!
In the past several years, the $J_c$ has been rapidly enhanced particularly for SrFe$_2$As$_2$(122) wires and tapes.


4.2K, 10 T
$J_c=1.2 \times 10^5$ A/cm$^2$
\( J_c \) (10 T) of the first 11m long SrFe\(_2\)As\(_2\) tape

-- by the scalable rolling process

Uniform wires can be fabricated

The first long wire-- 11 m

The average \( J_c \) of this long Sr122/Ag wire is \(~ 18400 \text{A/cm}^2\)

The fluctuations of the \( J_c \) is \(~5\%\)
Low material cost

High $J_c$ in Cu-sheathed SrFe$_2$As$_2$ tapes

At 4.2 K, 10 T
Transport $J_c$: $3.1 \times 10^4$ A/cm$^2$
Engineering $J_e$: $>10^4$ A/cm$^2$

We obtained nearly phase-pure Sr-122 tapes with hot pressing at 800°C for 30 minutes. This rapid fabrication method can effectively thwart the diffusion of Cu into polycrystalline Sr-122 core.

YBCO coated conductor

- NIN and Beijing University of Technology: Substrate
- Suzhou Advanced Materials Institute (SAMRI): MOCVD
- Shanghai Jiao Tong University: PLD
Development of Long-length & Textured Ni5W, Ni7W and Ni9W tapes for Coated Conductors

- **Thickness~66 μm**
- **Width=10 mm**
- **Length>500 m**

- **Sharp cube textured (~100%)** Ni5W tapes with the level of hundred meters were obtained by conventional metallurgy method.
- **Content of cube texture in Ni7W and Ni9W tapes reaches 99.5% and 94% respectively.**
Development of km-level YBCO CC by MOCVD/PLD

1. Electropolishing technology of substrate

Capability > 1000 m  Width of tape 12 mm
Speed: 60 m/h

The km-level metal substrate polishing system can produce tape with surface roughness 1 nm in SAMRI.
Development of km-level YBCO CC by MOCVD/PLD

2. IBAD-MgO buffer layer deposition technology

The IBAD system can deposit 10 nm MgO layer with sharp texture on km-level metal substrate.
Development of km-level YBCO CC by MOCVD/PLD

3. Sputtering-MgO buffer layer deposition technology

The sputtering system can deposit 30 nm MgO layer with sharp texture on km-level IBAD-MgO layer.
Development of km-level YBCO CC by MOCVD/PLD

4. MOCVD-YBCO layer deposition technology

- Capability > 1000m
- Width of tape 12mm
- Speed: 50-100 m/h
- Thickness of YBCO 1-3 μm

The MOCVD system can deposit 1-3 μm YBCO layer with sharp texture on km-level IBAD-MgO layer.
Development of km-level YBCO CC by MOCVD/PLD

5. PLD-YBCO layer deposition technology

The PLD system can deposit 1-3 μm YBCO layer with sharp texture on 500m-level IBAD-MgO layer.
4. Progress of superconducting applications

Magnet application

Electrical power application
The national major scientific and technological infrastructure construction project

- China Fusion Engineering Test Reactor (CFETR)
- Heavy Ion Research Facility (HIRF)
- Accelerator Driven Sub-critical System (ADS)

The big science instruments and facilities in HEP field require and push the R&D of superconducting technology in China.
The application of superconducting magnet in HEP

5T superconducting magnet for 1.8 GHz ECR ion source including 3 solenoids and 1 hexapole coil

3T superconducting magnet for HIRF controlling system

2T superconducting magnet for ADS system

The R&D groups in China can design and fabricate different NbTi and Nb$_3$Sn superconducting magnets for HEP application.
The 25T superconducting magnet

A 25 T superconducting magnet with a 10 T YBCO insert and a 15 T Nb$_3$Sn and NbTi outsert is being fabricated in IEE CAS.
A 9.4 T superconducting magnet is being designed and fabricated with a warm bore of 800 mm for neuroscience research. In IEE CAS
10kA HTS Cable: the design parameters

<table>
<thead>
<tr>
<th>No.</th>
<th>Items</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total length of the DC HTS power cable</td>
<td>362.4m</td>
</tr>
<tr>
<td>2</td>
<td>Total length of the cryogenic envelope / LN₂ flow pipe</td>
<td>350.1m / 367.4m</td>
</tr>
<tr>
<td>3</td>
<td>Length / out diameter of the termination</td>
<td>6.15m / 325mm</td>
</tr>
<tr>
<td>4</td>
<td>Out diameter of the DC HTS power cable</td>
<td>151mm</td>
</tr>
<tr>
<td>5</td>
<td>Layers of the cable core</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>Winding angle of the cable core</td>
<td>15° (with difference for each layer)</td>
</tr>
<tr>
<td>7</td>
<td>Total length of the HTS tapes used</td>
<td>46km</td>
</tr>
<tr>
<td>8</td>
<td>Heat loss of the cryogenic envelope / LN₂ flow pipe</td>
<td>2W/m / 1.0W/m</td>
</tr>
<tr>
<td>9</td>
<td>Segmentations of the cryogenic envelope / LN₂ flow pipe</td>
<td>Totally 8 segments</td>
</tr>
<tr>
<td>10</td>
<td>Dielectric type</td>
<td>Warm dielectric</td>
</tr>
<tr>
<td>11</td>
<td>Total heat loss of the DC HTS power cable system</td>
<td>2487W</td>
</tr>
<tr>
<td>12</td>
<td>Refrigeration type / capacity</td>
<td>LN₂ circulation / 4kW@77K</td>
</tr>
<tr>
<td>13</td>
<td>Designed critical current</td>
<td>12,500A</td>
</tr>
<tr>
<td>14</td>
<td>Rated current</td>
<td>10,000A</td>
</tr>
<tr>
<td>15</td>
<td>Rated voltage</td>
<td>1300V</td>
</tr>
<tr>
<td>16</td>
<td>Minimum bending radius</td>
<td>3.0m</td>
</tr>
</tbody>
</table>

The 360m/10kA cable was installed in ZhongFu electrolytic aluminium factory in 2013
Cryogenic envelope

- The cryogenic envelope has been divided into 8 segments;
- Each segment has a standardized joint at both ends;
- Just inserts type A joint into type B joint when integration;
- The static heat loss for the envelope is less than 0.8W/m;
- This integration design and assembly is a good way for long-distance HTS cables.
Cable terminator

- Modularization: each functional part is independent;
- Three functional parts: the main body, current lead, chamber.
Refrigeration system: Stiring cryo-cooler

- Total heat loss of cable: 2487W;
- Cryo-cooler: Stirling refrigerator;
- Total cooling capacity: 4kW@77K.

Stirling refrigerator and a backup refrigerator are employed for DC cable.
The HTS DC cable has been connected to the busbar for a alumina electrolyzer

Location of the DC cable: connects the rectifier with the bus bar
IEE: 10kA/360m HTS DC Power Cable

- The cable connects 110kV line via rectifiers;
- The cable was cooled down by Stirling cooler.
10kA/360m HTS Power Cable after Installation

The design of DC cable ensure the installation in complex environment
Tests of the Power Cable

Tests show that the Ic of Cable is larger than 12.5kA by 1uV/cm, and 2 hours of operation shows that the voltage drop in the cable is not changed.
IEE: HTS Power Substation

- **SMES:**
  - Quick power compensation;
  - Improve power quality;
  - Uninterrupted power.

- **Superconducting FCL:**
  - Suppress Fault current;
  - Enhance dynamic stability and reliability of the grid;
  - Increase transmission capacity;
  - Prolong life of the equipment.

- **HTS Power Transformer:**
  - Lower Operational loss;
  - Increase unit capacity.

- **HTS Power Cable:**
  - Lower transmission loss;
  - Increase transmission capacity.

○ Enhance stability and reliability;
○ Improve power quality;
○ Lower transmission losses.
IEE: HTS Power Substation
IEE: HTS Power Substation

First HTS Power Substation in Baiyin city, Gansu province
IEE: HTS Power Substation

Device ① – The 10.5kV/1MJ/0.5MVA High Tc SMES

Overview:
- Integrates functions of **active power filtration, reactive & active power compensation**;
- **First** in-grid-operation High Tc SMES in China for **more than one year**.

Main parameters:
- Rated voltage: 10.5kV;
- Stored energy: 1.08MJ;
- Output: 0.5MVA;
- Response time: ≤1ms;
- Conversion effic.: ≥90%;
- Voltage fluctuation: ≤1%;
- Power factor: 0.99.
IEE: HTS Power Substation

Device ② – The 10.5kV bridge-type SFCL

Overview:
- Energized in 2005;
- The fourth in the world;
- 3-Ø earthing tests conducted in power grid;
- Operation more than 20,000 hours by far.

Main parameters:
- Rated voltage: 10.5kV;
- Rated current: 1.5kA;
- Short-circuit current shrinking rate: 82% (from 3500A to 635A);
- Response time: 2ms;
- Recovery time: 12ms;
- Normal volt. Drop: 0.5%.
IEE: HTS Power Substation

Device ③ – The 630kVA HTS transformer

- **Overview:**
  - Energized in 2005;
  - Passed the industrial standard tests by the national authority;
  - Largest amorphous alloy HTS transformer core;
  - Operation more than one year in real grid.

- **Main parameters:**
  - Rated power: 630kVA;
  - Voltage: 10.5kV/0.4kV;
  - Current: 34A/909A;
  - Short-circ. resist. 2.45%;
  - Connection: Yyn0+d7;
  - Efficiency: 98.3%.

Losses decrease, capacity enhancement, …
IEE: HTS Power Substation

Device ④ – The 75m HTS power cable

• Overview:
  – Energized in 2004;
  – For multiple factories;
  – Operation more than 15,000 hours in the real power grid;
  – Stably and reliably.

• Main parameters:
  – Length: 75m;
  – Rated voltage: 10.5kV;
  – Rated current: 1.5kA;
  – DC critical current: 5kA;
  – Joint resistance: $10^{-7} \Omega$;
  – Heat loss of cryogenic envelope: 1.5W/m;
  – Min. bend. Diam.: 2.4m.
The progress of FCL in power grid

Current Rating: 800 A
Expected short-circuit current 50 kA

The saturated core Type 3 phase, 220 kV.

Time to open of 220kV FCL system <8ms

Energize recovery time of 220kV FCL system <600ms

The continuous operating time is more than 10 months.

Innopower Superconductor Cable Co. (Innopower)

The 220 kV FCL was put into operation at Tianjin electrical power company in 2013.
The progress of FCL in power grid

Current Rating: 3150 A
Rated voltage of grid: 550 kV

The 550 kV FCL DEMO is under construction at China Southern Power Grid.
Summary

1. The Chinese government input funds more than 600 Million RMB and industry input funds more than 700 Million RMB for R&D of superconducting materials and applications in the period of 12th Five-Year plan.

2. The LTS industry has been formed in China.

3. The YBCO and BSCCO tapes can meet the requirements of electrical power DEMO.

4. The Chinese government will support continuously the R&D of superconductivity in the period of 13th Five-Year plan (from 2016).
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INNOPOWER/ China Southern Power Grid
Thanks for your attention