Superconducting Cables Department of Russian Scientific R&D Cable Institute (JSC “VNIIKP”), Moscow, Russia.

- Who we are and our achievements:
- R&D in superconducting wires, cables and devices

By Vitaly Vysotsky, Head of department of superconducting wires and cables

July 2013
OUTLINE

• The Institute
• The Department – works, collaborations, products
• ITER works
• R&D in HTS cables and current carrying elements development, AC loss, theories, overloads, FCL, etc.
• Hydricity
• JSC “VNIIKP” conclusions
• Contact
The All Russian Cable Research and Development Institute-VNIIKP (Pronounce: vne-e-e-ka-pe) was organized in 1947.

It is the major research and development center of the cable industry in the former USSR and now in Russia. Staff ≥540 empl., total area – 43000 sq. m.

Area of R&D works in the Institute are from simple copper cables to high-end fiber optics and superconducting cables.

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The Department of Superconducting Cables has been organized in 1967 in Podolsk city, ~20 km to south from Moscow. It is the major R&D center and producer of any kind of superconducting cables in former USSR and now in Russia. Any kind of superconducting cables can be developed, studied and produced in our Department. Some specific superconducting devices were also developed in the Department. We have well qualified scientific, engineering technical and support staff. Currently, in total ~105 employed. We have modern cabling and research equipment, low temperature test facilities.
**The Department**

**Our tasks**

- **R&D:** whatever is more than one superconducting wire or tape: LTS cables, HTS assembled coating conductors, etc.;
- **Study:** of basic properties of LTS and HTS wires, stability, AC losses, quench, etc.
- **Developments:** for example power cables
- **Production:** any LTS and HTS cables and major is ITER TF conductors and PF cables

*i.e. we combine research, development and production*
1. ITER Program and CICC developments: VNIIKP bears the major responsibility in Russia for R&D of CICC for ITER program

2. Plus many R&D worldwide as developer and vendor of different CICC: for example in China Tokamak projects EAST, Korea K-Star project etc. Maximum unit length of the large CICC is up to 0.9 km.

3. We developed, produced and delivered many kinds of soldered, stabilized, transposed (Rutherford) and other superconducting cables for different projects worldwide (for example LHC-CERN, LDX-MIT, GSI-SIS100, and many others)

4. Our collaborators and customers are: IGC-Philips, MIT, LLNL, AMSC (USA), JAERI, Sumitomo (Japan), Ansaldo (Italy), Efremov Institute (St.Petersburg, Russia), ASIPP (China), CERN (Switzerland), Sultan Test Facility (Switzerland), Twente University (the Netherlands), GSI – Darmstadt, Germany, etc.
Besides ITER production we are participating in:
5. HTS superconducting power cable development was and is one of our major activities.
6. 3x200 m HTS superconducting power cable has been developed and is being tested.
7. HTS cables for ship propulsion system and for degaussing are in discussion
8. FCL switching elements and current carrying elements
9. Assembled HTS current carrying elements or assembled coating conductors cables (AC³)
10. HTS power transformer up to 1 MVA development
11. Hybrid energy transfer system with LH₂ and MgB₂ power cable
12. Etc., etc., etc…
Superconducting cables and conductors – some examples

Insulation by wrapping, braiding, etc.

Different kinds of transposed cables

Different kinds of CICC

The most miniature CICC in the world: outer diameter — 6.4 mm; 30 NbTi strands 0.5 mm each. Developed by VNIIP for SIS-100 project in GSI Darmstadt.
The Department – ITER

PF conductor: 52.3mm
TF conductor: 43.7mm

July 2013
- NbTi and Nb$_3$Sn strands are produced by ChMP
- Coating facilities have been upgraded:
  - Second cleaning line has been installed to increase productivity
  - Improvement of Ni and Cr technology
  - Soft technology and ecologically cleanliness
Two highly efficient spiral making machines installed to produce up to 100-200 m of spirals per day from 6 to 14 mm in diameter (10mm TF and 12 mm PF)

- We are ready to deliver spirals to other ITER teams (we sold the full set to US DA and are delivering to EU DA now)
The Department – ITER – Production facilities

Cabling – Machines

- Two high speed tubular machines (1-st and 2-d stages)
- Two medium planetary machines (3-d and 4-th stages)
- One large planetary machine (final 5-th stage) equipped by the set of special compacting calibers to increase density of a cable
- Final twisting takes 3-5 days for a 800 m cable
The jacketing line located in Protvino consists of a gallery with ~900 m length and a workshop where the equipment for welding, testing, compaction and coiling is placed.
Jacketing line is equipped by automatic welding machine, X-ray camera, vacuum test camera, TV for visual control of welds, vacuum control equipment, etc.
The major update of the test facility is the installation of the winder to prepare 4m transporting solenoid.

Two trial dummies have been made to tune the technological route.
After two trial ~400 m and 360 m length conductor have been made we finished 760 m Cu dummy conductor.

In Saturday Sept. 10, first 760 m Cu dummy has been delivered to Kurchatov Institute for vacuum test. By the end of September the coils was ready to be delivered to EU. In total 15 Uls of TF conductor have been produced by mid July, 2013.
760 m Cu dummy delivery

Up to now 15 TF conductors and 14 PF cables are ready. VNIIKP performs regular production of cables and conductors for ITER magnet system.

July 2013
R&D in HTS power devices, $A C^3$, FCL, etc.

Previous slides were about our LTS cabling R&D and production

The following will be about our HTS R&D and production
The first Russian program for introduction HTS devices to power industry has been signed in May 16 2007 by Mr. A. Chubais – the former head of the Russian company United Energy Systems.

HTS power cables was considered as – first priority

Fault current limiters, Transformers, Generators and machines (including synchronous compensators), SMES (LTS) were considered as well.

The program funding was on year by year basis. So far the real funding has been obtained for HTS power cables only as the most advanced and close to commercialization application.

Now part of works are switched to another Russian program: “Superconducting Industry” supported by State corporation “Rosatom”
Russian Program – HTS cables

Our route is:

Science ➔ Technology ➔ Production

Science
- Previous experience in LTS and HTS cables in VNIIKP
- Theoretical fundamentals development
- Basic wires studies
- Test facility and model/prototypes/witness samples with 5 m length studies
- Experimental test facility for powerful devices
- Experimental 30 m cable test

Technology
- Technological experiments
- Machines and equipment development
- Current leads (terminations) development

Production
- 3 x 200 m HTS power cable production

July 2013
Three major directions

- \( B \perp S \): \( \alpha = 90^\circ; \beta = \text{NA}; \gamma = 90^\circ \)
- \( B \parallel S \): \( \alpha = 0^\circ; \beta = 90^\circ; \gamma = \text{NA} \)
- \( B \parallel I \): \( \alpha = 0^\circ; \beta = 0^\circ; \gamma = 0^\circ \)

Perpendicular field

Parallel field

The dependence of the normalized critical current on the magnetic field with different orientation relative to tape surface ("tilt" angles) for the sample of L0V 1708322S wire.
Test facility and model/prototypes/witness samples with 5 m length studies

Cable models with length >3 m only, are representative for AC extensive tests. Edge phenomena spoil data for shorter cables. We use 5 m models.

LOW VOLTAGE HIGH CURRENT TEST FACILITY IS EQUIPPED BY:

5 m Flexible Test Cryostat

Power Supplies Set: Up To 2 and 6.5 kA DC. Up To 3.6 kA_{rms} AC

Computerized Data Acquisition System with 100-1000 and more samples per 50 Hz cycle provide high accuracy in digital measurements

Different measuring devices: amplifiers, flow meters, etc.

July 2013
In total 8+ models of 5-m cables have been tested up to now including first cable model with Russian 2G wire produced by SupeOx company.

First 5 m prototype.
AMSC Hermetic 1G wire.


2G model made from Super Power SCS4050 wire 2009.

July 2013
Science

Test facility and model/prototypes/witness samples with 5 m length studies

First 5 m prototype test, AMSC Hermetic 1G wire. 2 layers, 2005-2006

$I_c \sim 5$ kA DC – the full use of superconducting properties of basic HTS tapes

AC loses evaluated by different methods

$3.6 \text{ kA}_{\text{rms}}$ AC – quite uniform current distribution among layers $\pm 2.5\%$

July 2013
**Test facility and model/prototypes/witness samples with 5 m length studies**

**1G – 2G cables AC loss study and analysis, 2009-2012**


AC loss measured
First Russian 2G cable model with SuperOx tape

<table>
<thead>
<tr>
<th></th>
<th>In a layer</th>
<th>Average per tape</th>
</tr>
</thead>
<tbody>
<tr>
<td>First layer</td>
<td>2903 A</td>
<td>81</td>
</tr>
<tr>
<td>Second layer</td>
<td>3065 A</td>
<td>85</td>
</tr>
</tbody>
</table>
Current leads connected to cryostats and cryogenic system.

The 30 m three phase cable installed at the test facility.

The cable has been extensively tested from November 2008 till June 2009.


July 2013
DC test

Dependence of $I_c$ on temperature has been measured. $I_c \geq 4$ kA at different temperatures.

After full technological route has been passed superconducting properties of HTS tapes were kept intact!

July 2013
Our workshop is equipped by machines necessary to make all parts of an HTS cable. Technology includes also current leads – terminations development, cables assembling, etc.

Central spiral making machine

HTS tapes cabling machine

July 2013
After all scientific researches and technology developments we were ready for full size HTS cable production. 200 m cable has been developed and produced.

200 m cable design is quite similar to those of 30 m cable. Only superconducting shield made sufficient difference from 30 m cable design.

**Basic tapes:** Sumitomo Electric Di-BSCCO tapes with Cu alloy lamination

**Design:** Central spiral, copper former, copper protection for superconducting shield. Cable paper insulation.

**Cryostats:** NEXANS flexible cryostats with 92 mm outer diameter with PE protection cover up to diameter 102 mm.

July 2013
Production

Three phases of 200 m cable have been produced, assembled into three flexible cryostats and delivered to the test facility in early September 2009 and laid on the ground at the test site in R&D Center for Power Engineering.

Acceptance test has been successfully passed in the end of 2009.

Generally speaking, we would state that VNIIKP with collaborators are ready for industrial production of HTS power cables.

July 2013
Analytical model has been developed (A.L. Rakhmanov, V.S. Vysotsky, Yu.Ilyin - Cryogenics 40 N1 (2000) 19). Useful for HTS magnets!

Considers Quasi-Uniform Quench/Heating. Two regimes are possible - stable and unstable

Basic formulas

\[
\frac{T(t) - T_q}{T_f} = \frac{E(t) - E_q}{E_f} = \tan \frac{t - t_q}{t_f}, \quad I > I_q\; ; \quad \frac{T(t) - T_q}{T_f} = \frac{1 + g \exp(2t/t_f)}{1 - g \exp(2t/t_f)}, \quad I < I_q
\]

\[
\frac{I_q}{I_0(T_0)} = \frac{n}{n+1} \left[ \frac{hP(T_c - T_0)}{nE_q I_0(T_0)} \right]^{1/(n+1)}
\]

\[
T_q = T_0 + \frac{T_c - T_0}{n+1}, \quad T_f = (T_c - T_0) \sqrt{\frac{2I - I_q}{n+1} I_q} \; ; \quad E_q = \frac{hP_t}{I_0(T_0)n}, \quad E_f = nE_q \sqrt{\frac{2I - I_q}{n+1} I_q}
\]

\[
t_f = t_h \sqrt{\frac{2I_q}{I - I_q(n+1)}}, \quad t_h = \frac{CA}{Ph}
\]

“Critical current” – \(I_0\) is just very conditional parameter!

Not necessary to use any “superconducting” ideas 😊
More science – heat (quench) developments in HTS devices


Quasi-uniform model is adequate and working. It is universal due to scaling feasibility. Good for HTS magnets (devices) at T>10-30 K

And many more similar comparisons with experimental data, ours and from Literature

\[ \theta = \tan(\tau) \]

- YBCO thin film, 77.4K, 352 mA, temperature
- YBCO thin film, 77.4K, 1770 mA, voltage
- Bi2212 coil, 30K, 100A, bottom
- Bi2212 coil, 13 K, 160 A, middle
- Bi2223, textolite bobbin, 40K, 80A, TCD
- Bi2223, copper bobbin, 60K, 70A, TCC
- Pancake coil, 20K, 142 A, TC3
- Pancake coil, 40K, 102 A, TC3, heat drains
- Pancake coil, 62K, 55 A, TC3, heat drains
- Pancake coil, 80K, 26 A, TC3

July 2013
Our theoretical studies shows, that due to strong non-linearity of HTS the blow-up regimes with the heat localizations are possible. V.S. Vysotsky et al, ASC-2002, EUCAS – 2003 and ASC-2004.
More science – overload conditions in HTS tapes useful for FCL and quench protection

At conditions $I \gg I_c$ in LN2 bath, switch of cooling conditions take place, Experimental and theoretical studies has been performed.

**Useful for FCL and quench of cables.**


July 2013
1. Demands: 10 kA (400 A/mm²) at 4.2K 20T, at helium temperatures for future accelerators and magnets
2. Few kiloAmps (and kV), low losses for electro-technical devices
3. Some developments are necessary – this is our future job to be done
4. For example: compacted multilayer twisting, twisted staked tapes, Roebel

Modest overall current density (but very good stability)
Not transposed (if changing twist direction with each layer) – relatively slow field change
Simple technology
Cost almost equal to cost of basic wires
**Good for magnets, SMES, devices with slow current change**

High overall current density (stability could be good if added stabilizing tapes, or pack to stabilizer)
Not transposed
Simple technology
Cost almost equal to cost of basic wires
**Good for high current high field magnets, may be FCL**

High overall current density (but stability ???)
Transposed with low losses (may be??)
Complicated technology
Cost at least twice as much because of one half of wide superconductor one should through away.
**Good for accelerators and magnets with fast field change?**

July 2013
Couple types were made with YBCO tapes from Super Power and tested from July 2013:

- Former $\varnothing$ 11 mm, 14 tapes, 2 layers
  - $I_c$ (s.f., 77 K) ~ 1505 A (~100A per tape – OK with single tape data)
  - $J_c$ (s.f., 77 K) ~ 15A/mm²
  - $J_c$ (s.f., 4.2 K) ~ 75A/mm² – could be expected, too low

But we can reduce diameter of former, increase number of tapes, etc.

Not so high $J_c$, but we could try to increase. We could need it for HTS transformer, but it is not well transposed.

We found another solution to make simple transposed windings for HTS transformers.
Current carrying elements with 2-G HTS

Analysis of stacked – twisted tapes – current reduction.

With number of tapes increased the current per tape reduces

This phenomenon could be reduced and current increased if to put some gaps between tapes.

Works with compact cables (multi-twisted and staked-twisted) will be continued in framework of Russian program “Superconducting industry” and others

July 2013
Study of resistance/temperature rise in short samples and in small FCL model (220V - 380 V, 400A), demonstrated possibility of scaling of short sample data to bigger FCLs. Normalized voltage could be determined as:

\[ v = \frac{V_0}{l} = \sqrt{\frac{\rho \cdot C_p \Delta T}{\Delta t}} \]
First in the world experimental prototype of the hybrid energy transport system:

Hydricity = Hydrogen + Electricity

Paper 2LA-01 at ASC-2012

Very old idea that is back to 70-ties, but on papers only. We did experiment!

July 2013
Hydricity
Energy transfer with liquid hydrogen and superconducting cable – hybrid energy transfer system

Experiment!

**TASKS:**

- To chose the proper superconductor
- To develop and make superconducting cable with it
- To develop and produce liquid hydrogen cryogenic line
- To insert a cable inside cryogenic line and connect to cryogenics and electricity
- Bring to test facility with liquid hydrogen
- Make tests

**MAJOR GOAL, TO UNDERSTAND:**

- What is MgB2, its manufacturability and how to work with it
- How to work with LH2
- To get the first experimental data about hybrid energy transport systems
<table>
<thead>
<tr>
<th>Type - Superconducting technology</th>
<th>Basic material, $T_c$</th>
<th>Cryogen and its temperature</th>
<th>Prices US$ per 1kA-m</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTS – metallurgy</td>
<td>NbTi - alloy ~ 10K</td>
<td>Liquid helium at 4.2 K and below</td>
<td>Up to 3-5$ @ 4.2 K</td>
</tr>
<tr>
<td>LTS – metallurgy</td>
<td>Nb$_3$Sn – compound ~ 18 K</td>
<td>Helium up to 8-10 K and below</td>
<td>Up to 15$ @ 4.2K</td>
</tr>
</tbody>
</table>
| HTS 1 generation (Powder in tube – metallurgy) | Ceramic Bi$_2$Sr$_2$Ca$_{n-1}$Cu$_n$O$_{2n+4}$ (Bi-2223,Bi-2212) ~90-110 K | Liquid nitrogen at 77 K and below (with other cryogens) | About 120-150$ @ 77 K
About 40-50$ @ 20 K |
| HTS 2 generation (Long coated conductors - electronics) | Ceramic YBa$_2$Cu$_3$O$_{7-d}$ ~90 K | Liquid nitrogen at 77 K and below (with other cryogens) | About 300-500$ @ 77K
About 80-150$ @ 20K |
| Magnesium diboride - (Powder in tube – metallurgy) | MgB$_2$ – compound ~39 K | Liquid hydrogen and below (with other cryogens) | About 5$ @ 20 K |

Magnesium diboride: now available, has high parameters (overall current density about 2-7$ \cdot 10^4$ A/cm$^2$ at LH$_2$ temperatures) and most important: pretty cheap!

July 2013
Superconducting cable

Basic tape: 3.65 mm x 0.65 mm MgB₂, Fe barrier, Ni matrix, Cu stabilizer
Produced by Columbus superconductor, Genova, Italy

Estimated: I_c (20 K, s.f.) ~520-540 A
Later measured: I_c(20K, s.f.)=529 A

Cable: five tapes, two layers, total length 10 м, copper stabilization ~90 мм² for each layer
Insulation – 10 layers of Kapton, δ~1 мм, estimated as enough for 20-40 kV

July 2013
$I_c$ non-uniformity has been observed but results in wires are better than specifications from Columbus Superconductor. Paper 2MPC-11 at ASC-2012
The cable has been made with standard cable equipment with technologies similar to those used for HTS cables.
General view of the hybrid transport system

July 2013
Tests at the DBCA, November 2011
Tests process

General view of the system

DAS monitor

Control computer

Liquid hydrogen input

Hydrogen afterburner

July 2013
Total cooling time ~380 s.
To cool the system it was used ~ 2.3 kg of LH$_2$.
Estimated heat losses were below 10±2 W/m (good for LH$_2$), current lead losses at 2600 A~300 W.
Temperature at measurements were form 20 K to 26 K, pressures from 0.12 to 0.5 MPa
Temperatures variations along a cable from 0.2 K to 0.8 K depending on flow rate

LH$_2$ flow from 10 g/s to 250 g/s.
Test results – superconductivity

V-I characteristics at different temperatures have been measured. Data about critical current were obtained.

Ic(T) dependence
Data from wire supplier and from measurements of short samples coincides well with cable’s data.

July 2013
HYDRICITY CONCLUSIONS - I

- MgB$_2$ from CS has a good manufacturability and could be used for industrial cable production. **Superconducting parameters are good as well**

- Liquid hydrogen cryogenic line with special current leads has been developed – **works well**

- Developed, produced and tested **MgB2 superconducting cable** with 10 m length with currents ~ 2000-2600 A.

- First hydrodynamic and superconducting data of the hybrid energy transport system **has been obtained**

- With rather modest size of a system 30MW (thermal) +50MW (electrical) = 80 MW (total) power could be delivered now and up to 150-180 MW with increasing of HTS tapes number.
First in the world **experimental prototype** of hybrid energy transport system has been developed and tested.

From this real experiment we can get data that permit to make evaluations and to plan the next developments.

Our nearest plans: longer **flexible** line, high voltage test, more hydrodynamic and superconducting data.

New flexible cryostat and cable have been made.

Test is planned to the end of August.
We have:

• **Great experience in any superconducting cables, current carrying elements and other devices R&D and production, both LTS and HTS**

• **A lot of practical results that can be used for future works**

• **We got practical experience and practical data for MgB$_2$ cable and wires**

• **We could share our experience and to work together in future**

• **Tell us what would you need?**

• **And we will do this for you! 😊**

July 2013
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MgB2 from Grid Logic

![Graphs showing the relationship between Ic (A) and T (K).](image)