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 Institute

(background: our headquarter at shosse Entuziastov 5 in Moscow)

Russian Scientific R&D Cable Institute (JSC "VNIIKP")

- 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.

The Department

(background: our building in Podolsk city)

Superconducting Wires and Cables Department

- 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 produced 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

The Department – Our experience

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.

The Department – Current projects

Besides ITER production we are participating in:

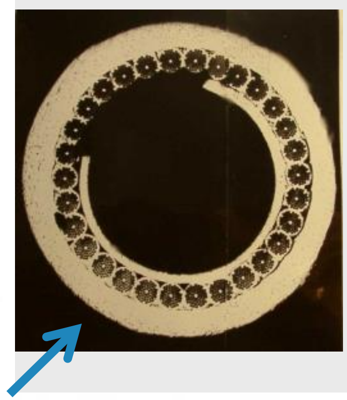
5. HTS superconducting power cable development was and is one of our major activities.
6. 3x200 m HTS superconducting power cable has been developed and is being tested.
7. HTS cables for ship propulsion system and for degaussing are in discussion
8. FCL switching elements and current carrying elements
9. Assembled HTS current carrying elements or assembled coating conductors cables (AC^3)
10. HTS power transformer up to 1 MVA development
11. Hybrid energy transfer system with LH_2 and MgB_2 power cable
12. Etc., etc., etc…

Superconducting cables and conductors – some examples

Insulation by wrapping, braiding, etc.

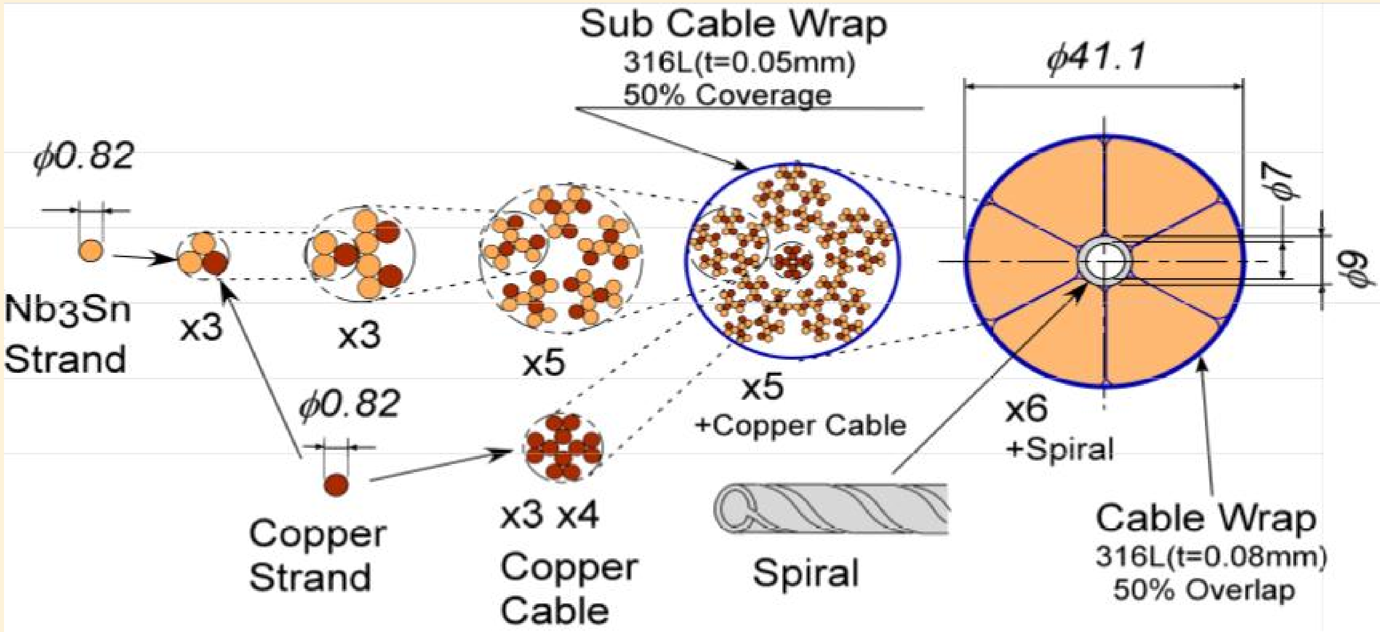
Different kinds of transposed cables

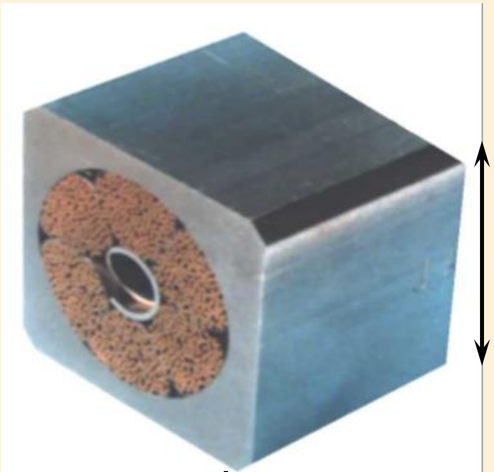
Different kinds of CICC



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

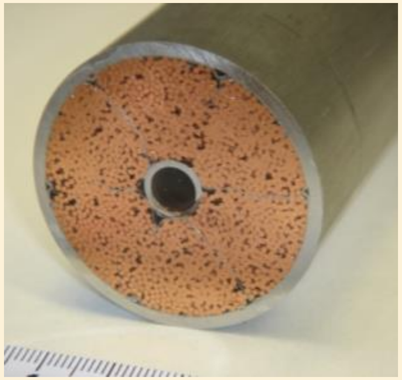
The Department – ITER





52.3mm

PF conductor



43.7mm

TF conductor

The Department – ITER – Production facilities

- NbTi and Nb_3Sn 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 cleanness

Cleaning line

Ni coating line

Cr coating line

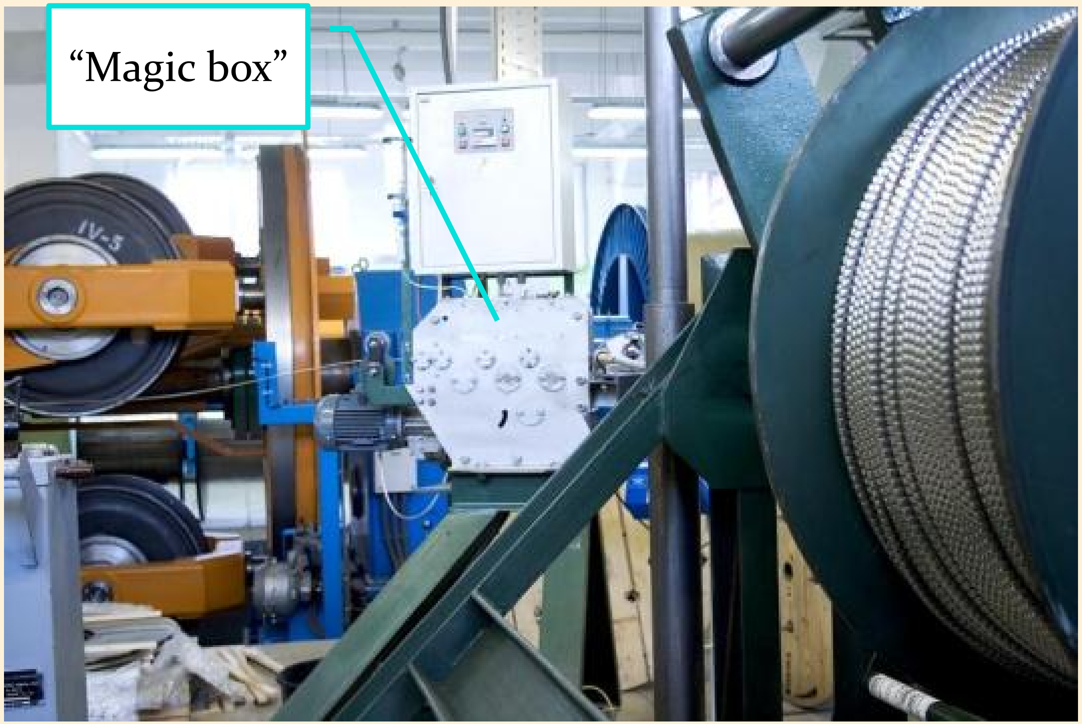
Evaporator and distiller

The Department – ITER – Production facilities

Cabling – spiral production

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)

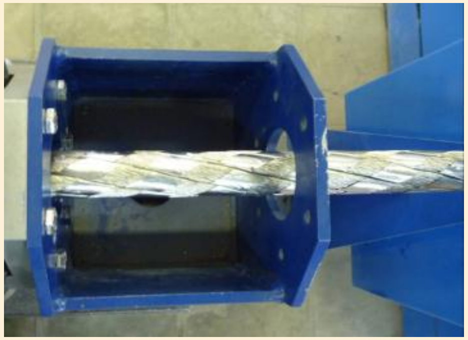
- We are ready to deliver spirals to other ITER teams (we sold the full set to US DA and are delivering to EU DA now)



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



JACKETING LINE

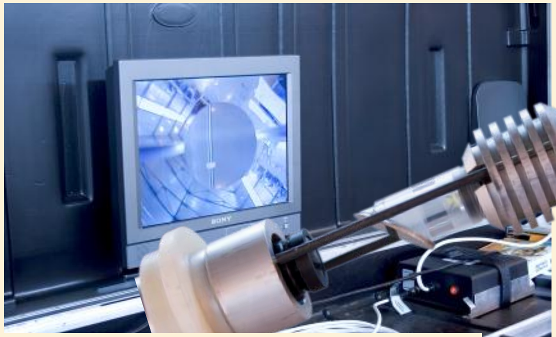
- The jacketing line located in Protvino consists of a gallery with ~900 m length and a workshop where the equipment for welding, testing, compaction and coiling is placed

The Department – ITER – Production facilities

JACKETING - Equipment

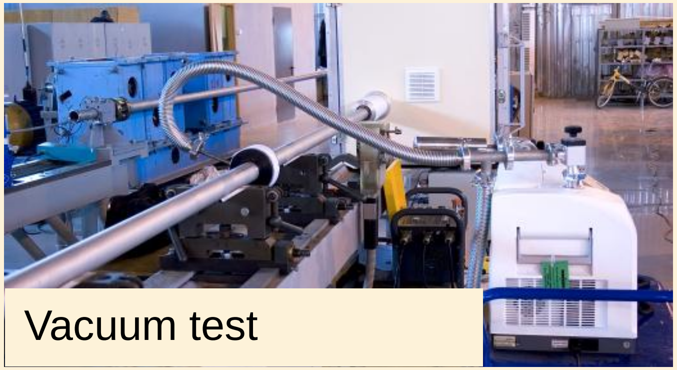
- Jacketing line is equipped by automatic welding machine, X-ray camera, vacuum test camera, TV for visual control of welds, vacuum control equiment, etc.

Welding head



Visual test set

X-Ray camera



Vacuum test

Laser marker

JACKETING - Winder

- 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


Winder

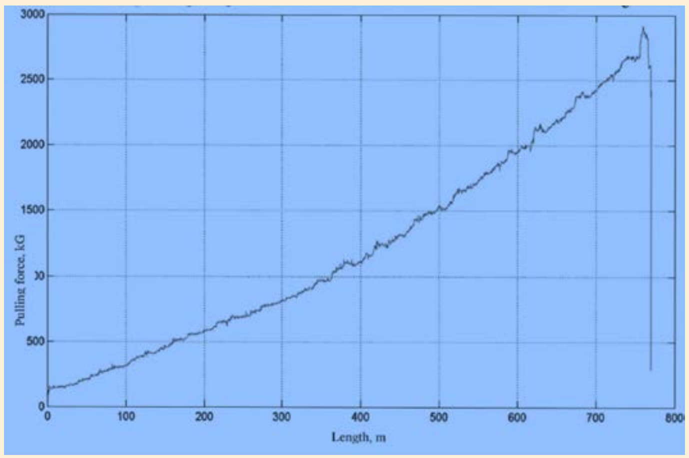

Bending device


Trial conductor on the winder

The Department – ITER – Production facilities

JACKETING – 760 m Dummy finished

- After two trial ~400 m and 360 m length conductor have been made we finished 760 m Cu dummy conductor



Pulling force diagram

Coil in shells

Coil packed

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.

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

The following will be about our HTS R&D and production

Russian Program for HTS power devices

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 – <u>first priority</u>

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

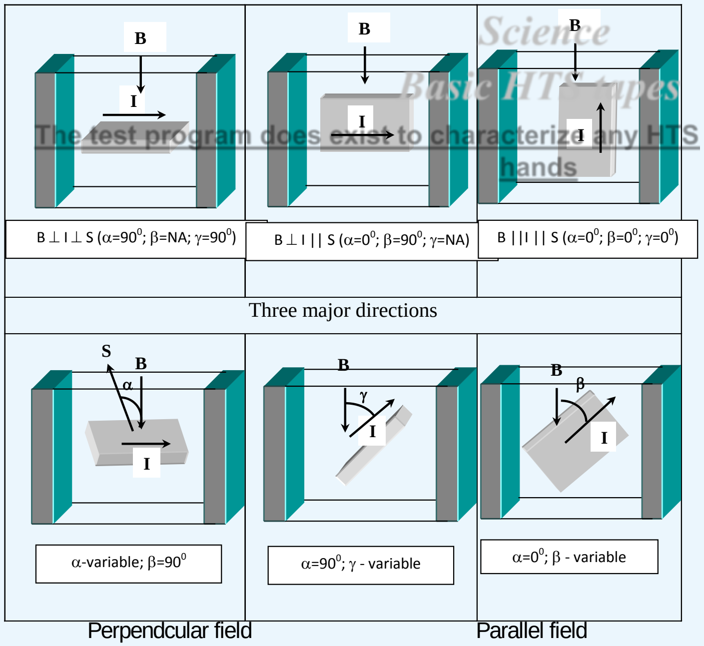
Production

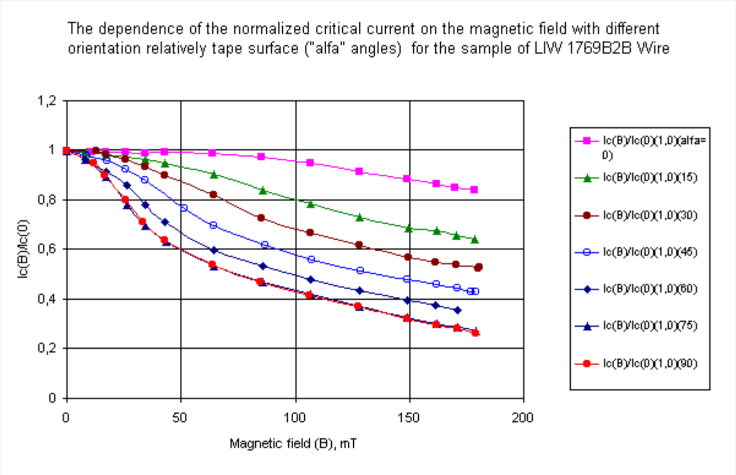
- 3 x 200 m HTS power cable production

Лекция 2

Science Basic HTS tapes

The test program does exist to characterize any HTS hands

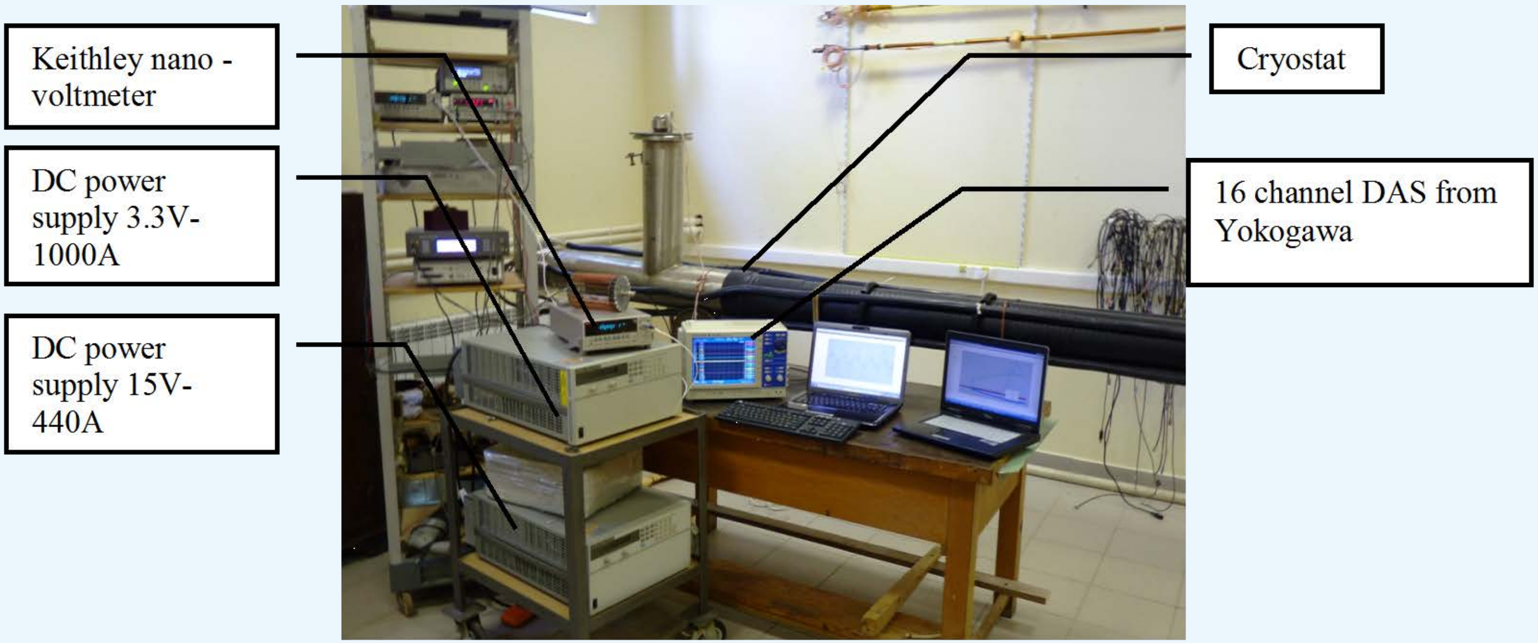




Science

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.

Science

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

First 5 m prototype..
AMSC Hermetic 1G wire.
2005-2006.

Witness sample of 30 m experimental; cable. Sumitomo CT-OP wire 2007-2008.

2G models made from AMSC 344B wire 2009, 2010.

Witness sample of 200 m cable. Sumitomo 1G DI-BSCCO wire, 2009.

2G model made from Super Power SCS4050 wire 2009.

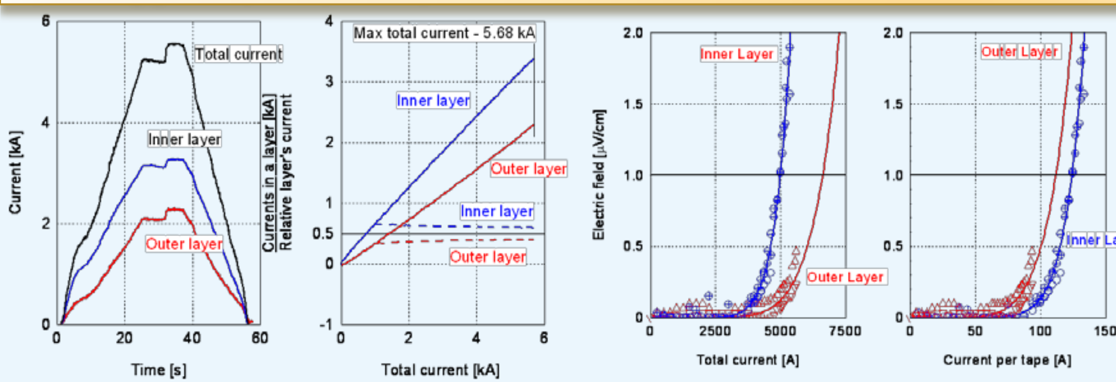
In total 8+ models of 5-m cables have been tested up to now including first cable model with Russian 2G wire produced by SupeOx company

Science

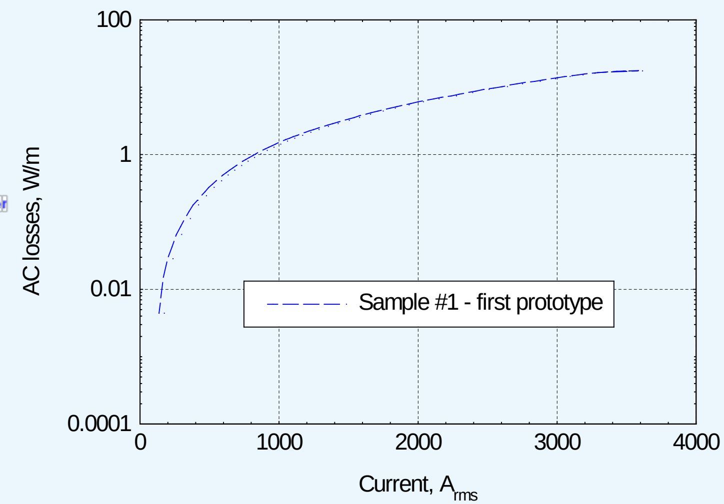
Test facility and model/prototypes/witness samples with 5 m length studies

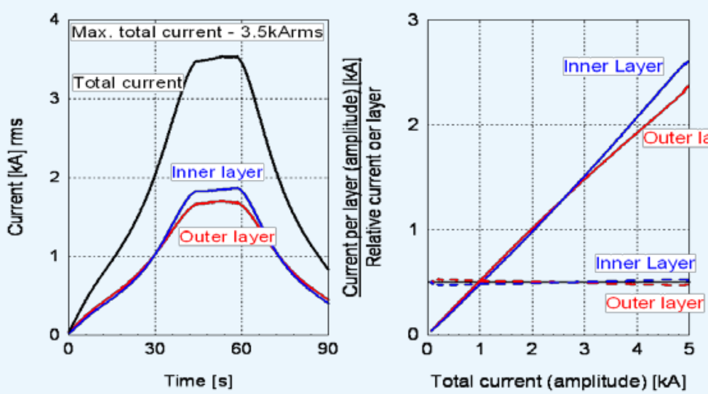
First 5 m prototype test, AMSC Hermetic 1G wire. 2 layers, 2005-2006

See in: V. E. Sytnikov, et al The 5m HTS Power Cable Development and Test, IEEE Trans on Appl Supercon. Vol. 17, N2, pp.1684-1687, **2007**



I_c~5 kA DC – the full use of superconducting properties of basic HTS tapes





3.6 kA_{rms} AC – quite uniform current distribution among layers ±2.5%

AC loses evaluated by different methods

See in: V. E. Sytnikov, et al., IEEE Transactions on Applied Superconductivity, Vol.19, N3, **2009**, pp.1706-1709

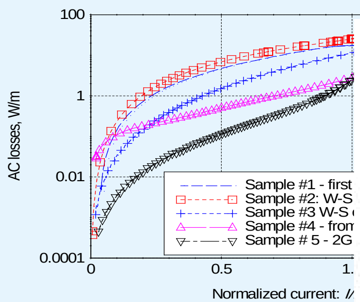
V. S. Vysotsky, et al, AC Loss and Other Researches with 5 m HTS Model Cables, IEEE Transactions on Applied Superconductivity, Vol.21, N3, pp.1001-104, **2011**

Science

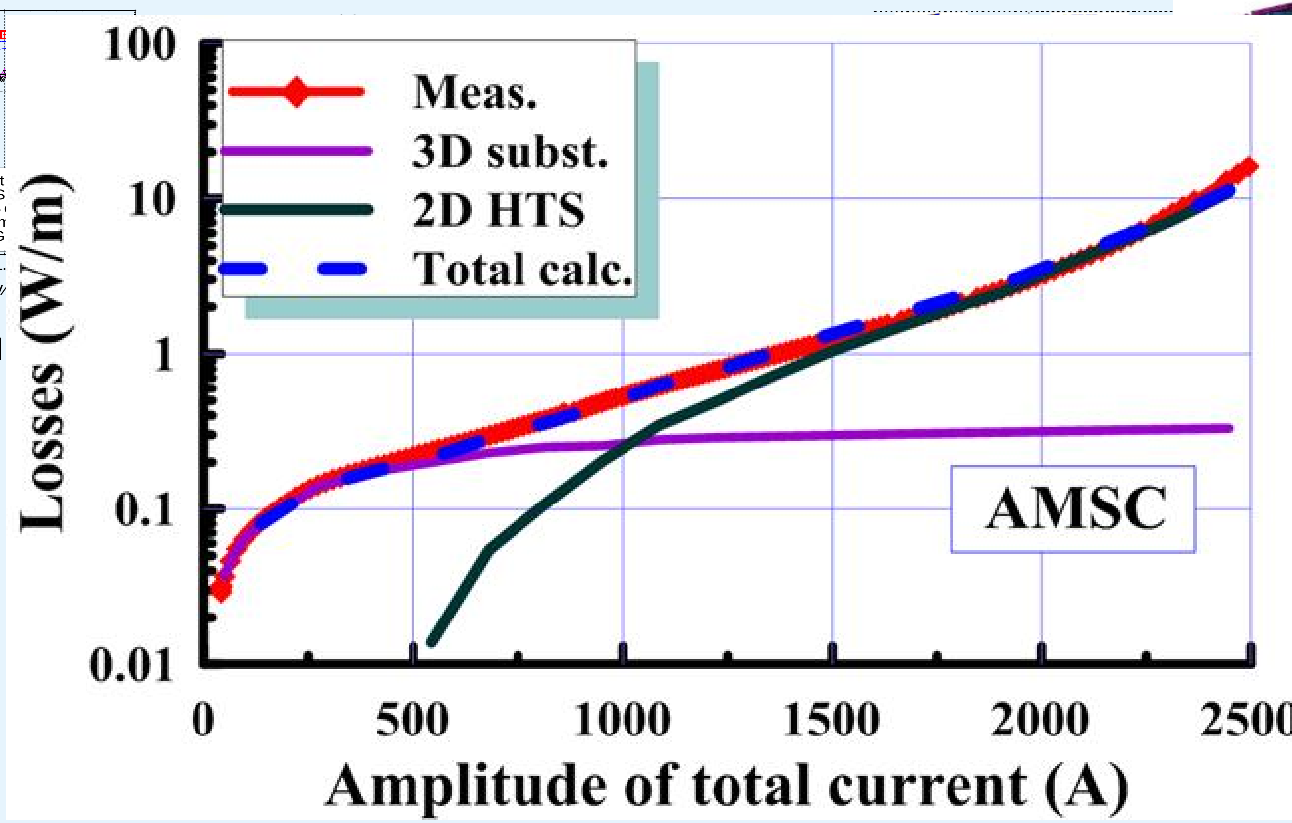
Test facility and model/prototypes/witness samples with 5 m length studies

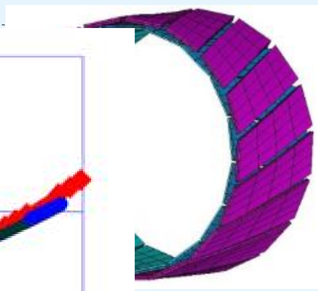
1G – 2G cables AC loss study and analysis, 2009-2012

See in: V. S. Vysotsky, A. A. Nosov, S. S. Fetisov, K. A. Shutov, AC Loss and Other Researches with 5 m HTS Model Cables, IEEE Transactions on Applied Superconductivity, Vol.21, N3, pp.1001-104, 2011,
V.V. Zubko, S.S. Fetisov and V.S. Vysotsky, Influence on AC losses in power cables of geometry of superconducting layers and magnetism of substrate of 2G HTS tapes. Paper 3LPD-10 at ASC-2012, Portland, Oct.2012



AC loss measu



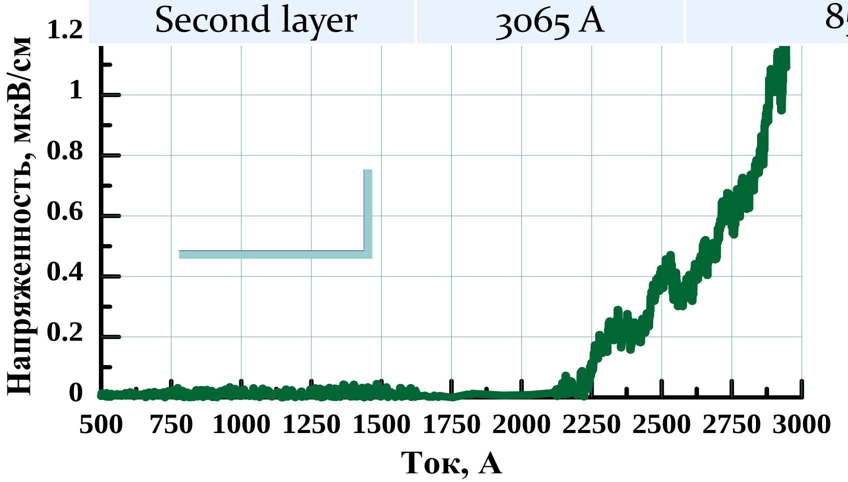


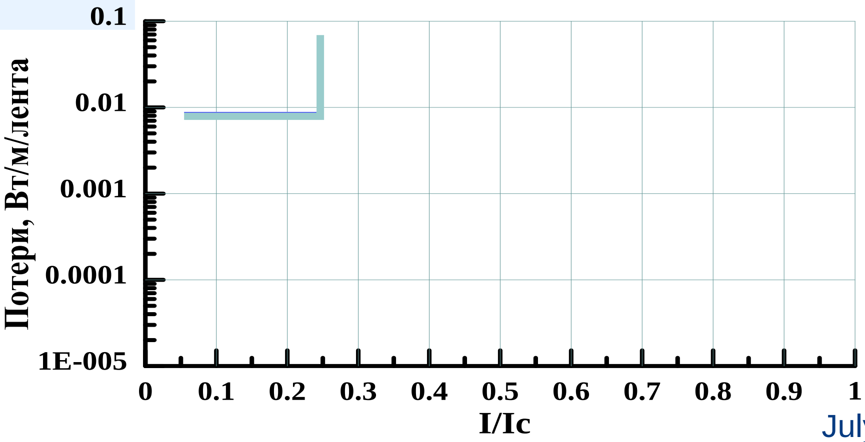
M model

Science

First Russian 2G cable model with SuperOx tape

I_c	In a layer	Average per tape
First layer	2903 A	81
Second layer	3065 A	85





Science

Experimental 30 m cable test

Current leads connected to cryostats an cryogenic system.

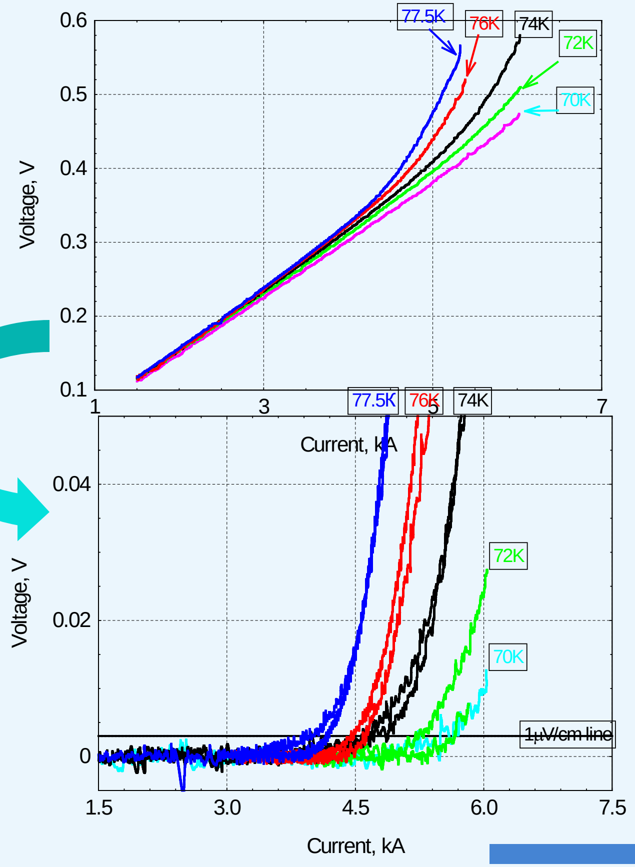
The 30 m three phase cable installed at the test facility.

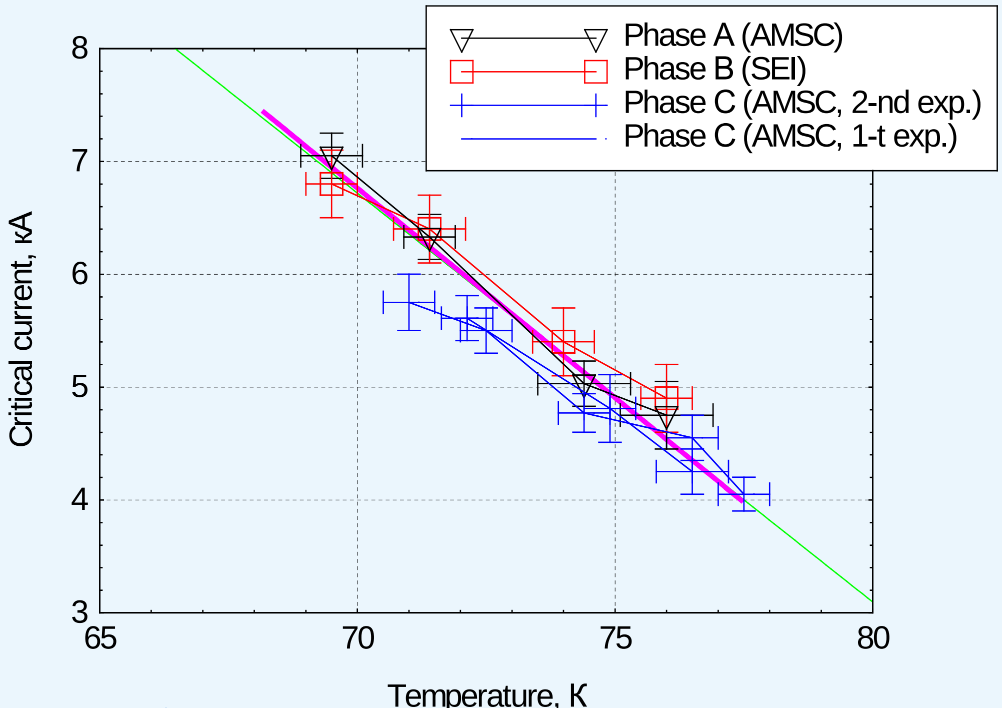
The cable has been extensively tested from November 2008 till June 2009

Test results see in: V. E. Sytnikov, V. S. Vysotsky, et al ”Cryogenic And Electrical Tests Results Of 30 M HTS Power Cable”, (ADVANCES IN CRYOGENIC ENGINEERING: Transactions of the Cryogenic Engineering Conference – CEC 2009, VOL. 55)

DC test

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





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

Technology - machines

Our workshop is equipped by machines necessary to make all parts of an HTS cable

Central spiral making machine

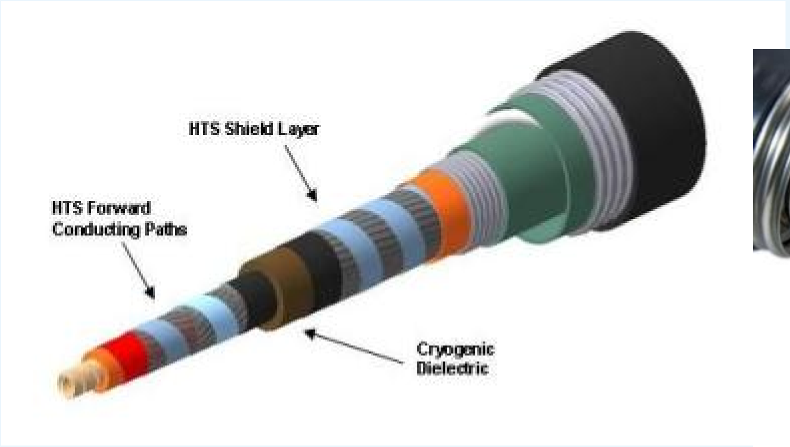
HTS tapes cabling machine

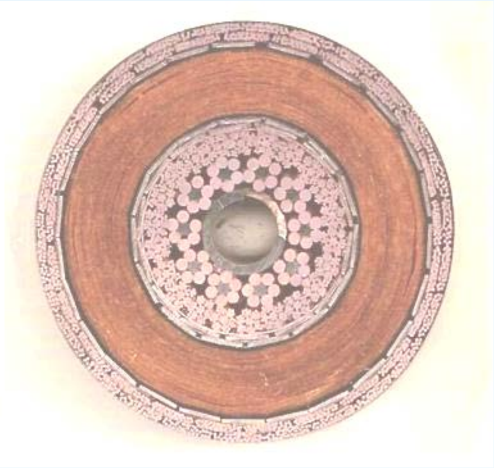
Technology includes also current leads – terminations development, cables assembling, etc.

Production

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

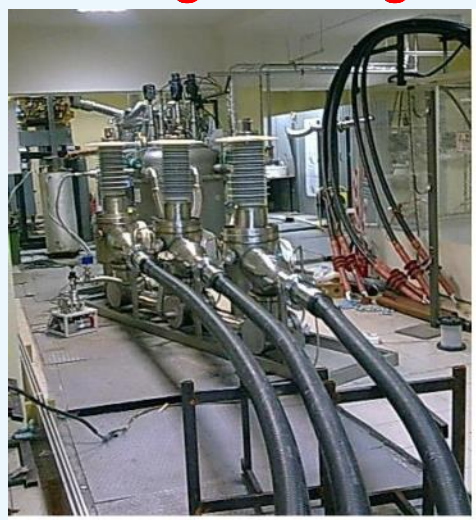
Basic tapes: Sumitomo Electric Di-BSCCO tapes with Cu alloy lamination

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.

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.

More science – heat (quench) developments in HTS devices

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

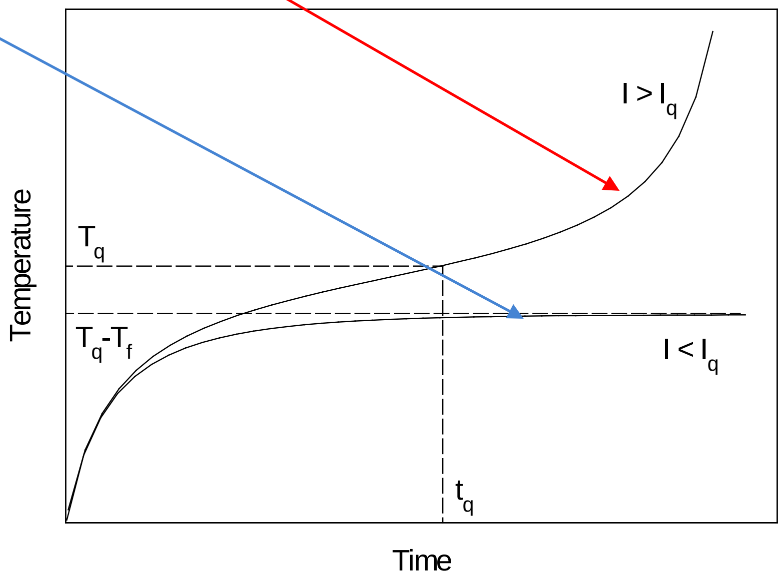
Basic formulas

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

$$\frac{I_q}{I_0(T_0)}=\frac{n}{n+1}\left[\frac{hP(T_c-T_0)}{nE_0I_0(T_0)}\right]^{1/(n+1)}$$

$$T_q=T_0+\frac{T_c-T_0}{n+1},\quad T_f=(T_c-T_0)\sqrt{\frac{2|I-I_q|}{(n+1)I_q}};\quad E_q=\frac{hPT_c}{I_0(T_O)n},\quad E_f=nE_q\sqrt{\frac{2|I-I_q|}{(n+1)I_q}};$$

$$t_f=t_h\sqrt{\frac{2I_q}{|I-I_q|(n+1)}};\quad t_h=\frac{CA}{Ph}$$

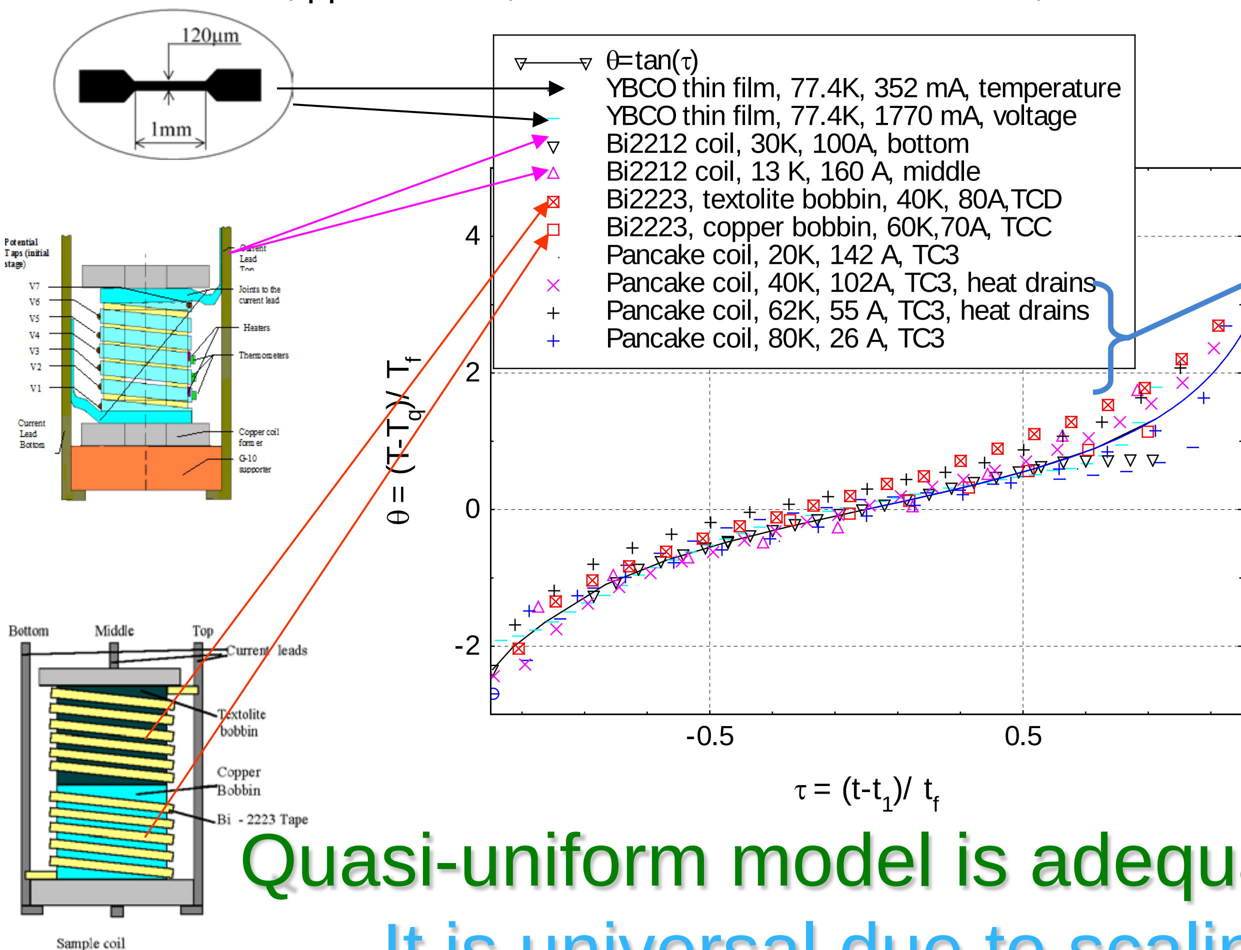


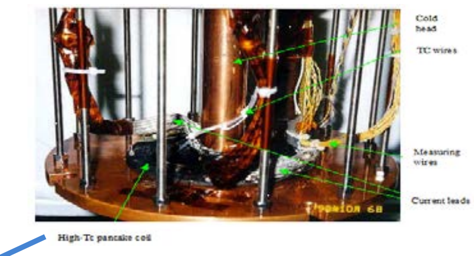
"Critical current"– I_o is just very conditional parameter !

Not necessary to use any "superconducting" ideas ☺

More science – heat (quench) developments in HTS devices

See review: V.S. Vysotsky, A.L. Rakhmanov and Yu. A. Ilyin, NOVEL APPROACHES TO DESCRIBE STABILITY AND QUENCH OF HTS DEVICES, In: Superconductivity Research Developments, ISBN: 978-1-60021-848-2 Editor: James R. Tobin, pp. 221-237, 2007 Nova Science Publishers, Inc.





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

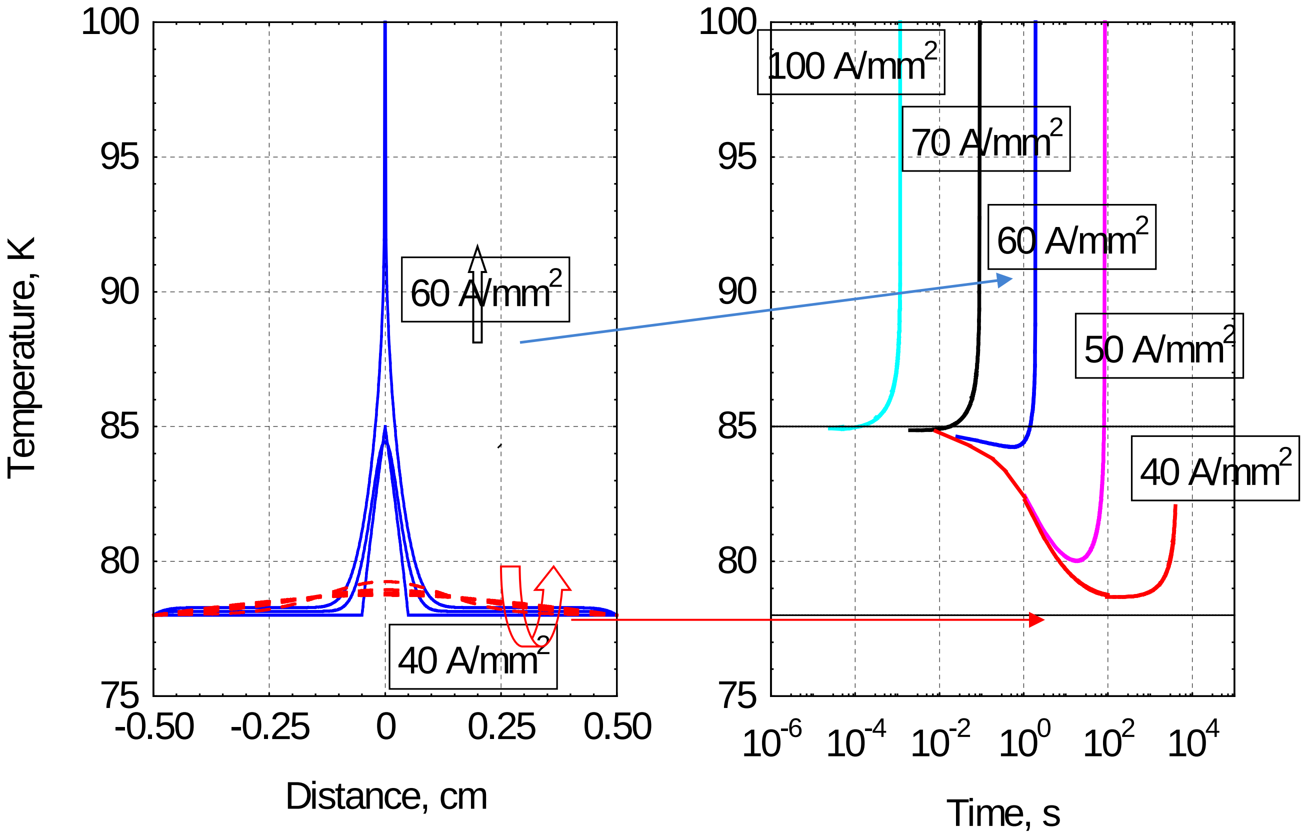
Quasi-uniform model is adequate and working.

It is universal due to scaling feasibility.

Good for HTS magnets (devises) at T>10-30 K

More science – non-uniform heat developments in HTS cables

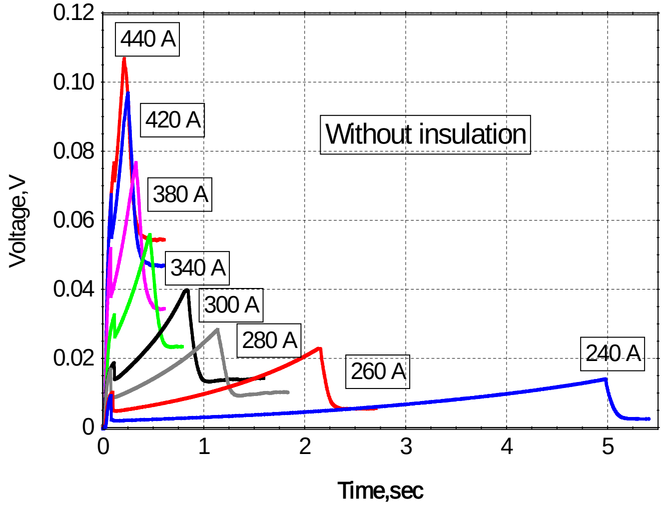
See: V.S.Vysotsky, V.V.Repnikov, E.A.Lobanov, G.H. Karapetyan and V.E.Sytnikov Heating Development Analysis in Long HTS Objects – Updated Results, J. Phys.: Conf. Ser. 43 877-880, 2006 (Proceedings EUCAS – 2005) 2006 J. Phys.: Conf. Ser. 43 877, doi:10.1088/1742-6596/43/1/214



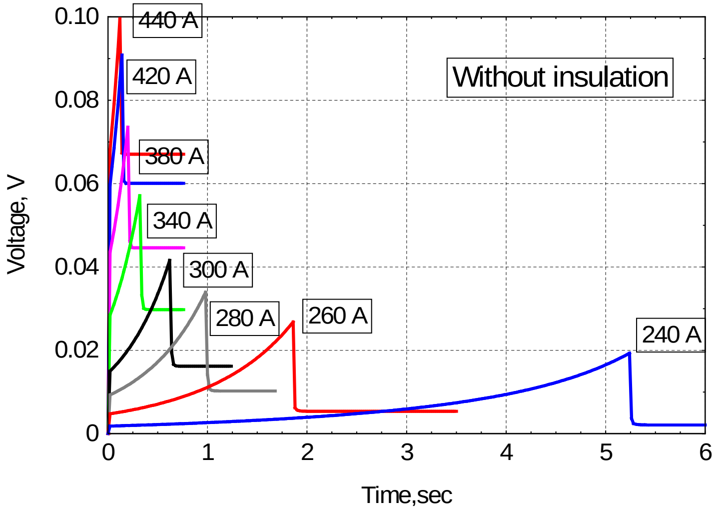
Our theoretical studies shows, that due to strong non-linearity of HTS the blow-up regimes with the heat localizations are possible. V.S. Vysotsky et al, ASC-2002, EUCAS – 2003 and ASC-2004

More science – overload conditions in HTS tapes

useful for FCL and quench protection



Measuring

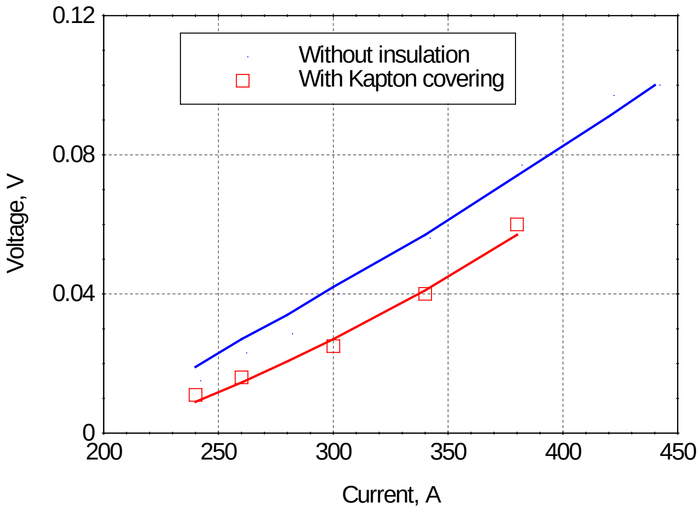


Simulation

At conditions I>>Ic in LN2 bath, switch of cooling conditions take place, Experimental and theoretical studies has been performed.

Useful for FCL and quench of cables.

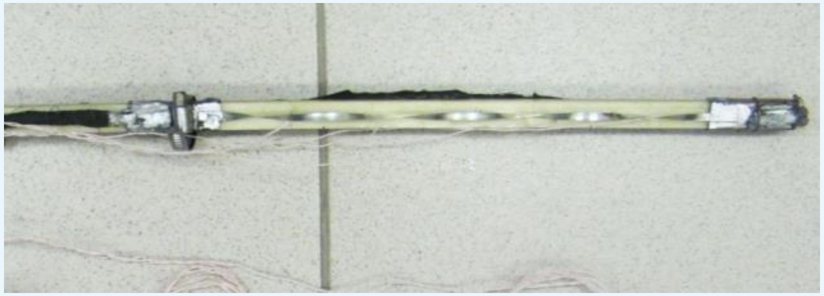
S.S. Fetisov, V.S. Vysotsky, V. V. Zubko, HTS Tapes Cooled by Liquid Nitrogen at Current Overloads, IEEE Transactions on Applied Superconductivity, Vol.21, N3, pp.1323-1327, **2011**.



Comparison

Assembled coated conductors cables what to do? Future.

1. Demands: **10 kA (400 A/mm^2) 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?

Current carrying elements with 2-G HTS

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

Former ∅ 11 mm,
14 tapes, 2 layers
I_c(s.f.,77 K)~1505 A (~100A per tape – OK with single tape data)
$J_{c\ overall}$(s.f.,77 K)~15A/mm^2
$J_{c\ overall}$(s.f.,4.2 K)~ 75A/mm^2 –could be expected, too low
But we can reduce diameter of former, increase number of tapes, etc.

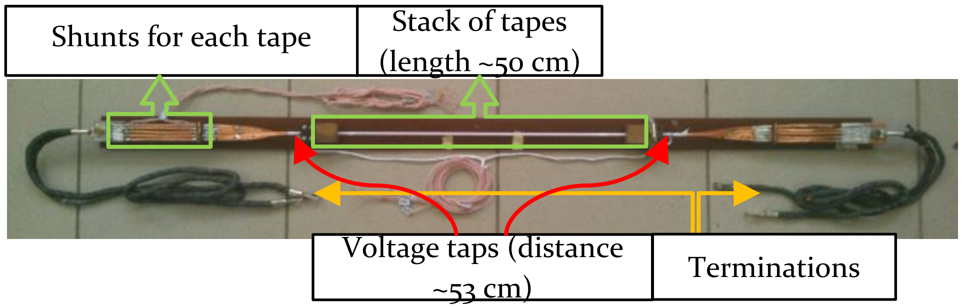
Not so high J_c, but we could try to increase. We could need it for HTS transformer, but it is not well transposed

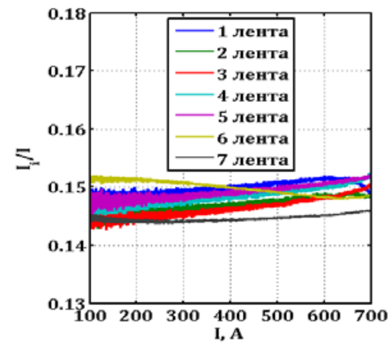
We found another solution to make simple transposed windings for HTS transformers

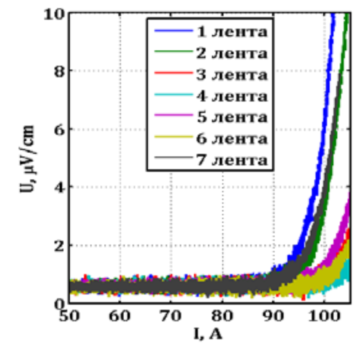
ВНИИКП
VNIIKP

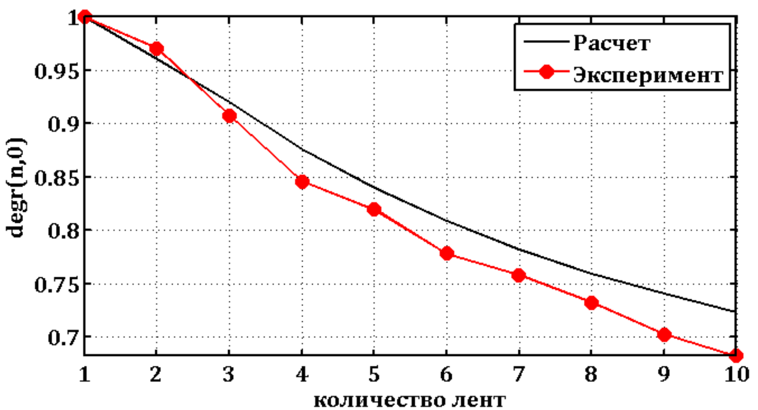
Current carrying elements with 2-G HTS

Analysis of stacked – twisted tapes – current reduction.

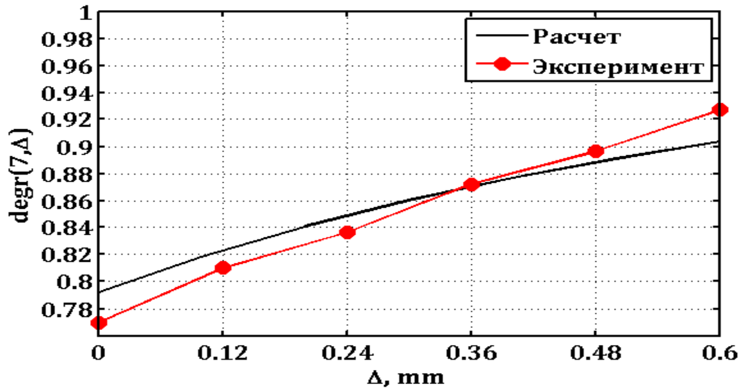








With number of tapes increased the current per tape reduces

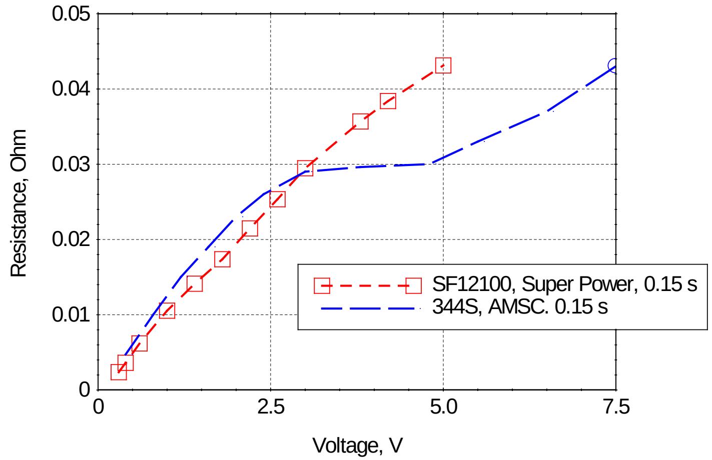


This phenomenon could be reduced and current increased if to put some gaps between tapes.

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

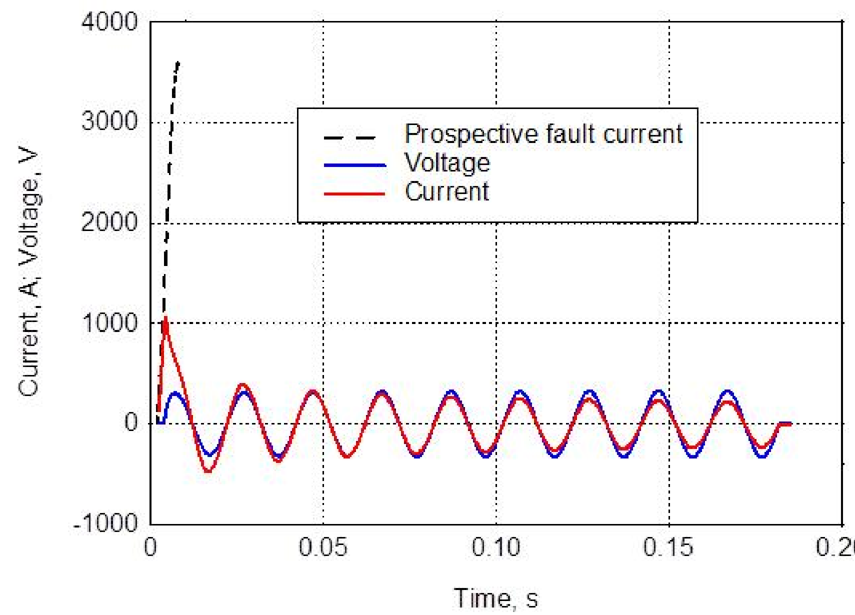
Small FCL model

Resistance (temperature) rise in HTS 2-G tapes



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:

$$v = V_0 / l = \sqrt{\frac{\rho \cdot C_p \Delta T}{\Delta t}}$$



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!

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 MgB_2, its manufacturability and how to work with it*
- *How to work with LH_2*
- *To get the first experimental data about hybrid energy transport systems*

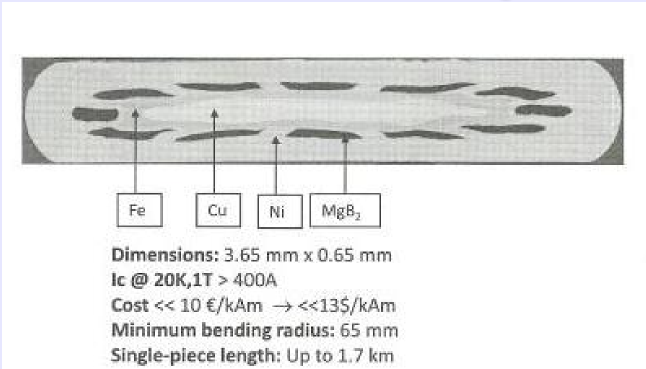
Superconductor's choice

Type - Superconducting technology	Basic material, T_c	Cryogen and its temperature	Prices US$ per 1кА·м
LTS – metallurgy	NbTi - alloy ~ 10K	Liquid helium at 4.2 К and below	Up to 3-5$ @ 4.2 К
LTS – metallurgy	Nb_3Sn – compound ~ 18 K	Helium up to 8-10 К and below	Up to 15$ @ 4.2К
HTS **1** generation (Powder in tube – metallurgy)	Ceramic $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$ (Bi-2223,Bi-2212) ~90-110 K	Liquid nitrogen at 77 К and below (with other cryogens)	About 120-150$ @ 77 К About 40-50$ @ 20 К
HTS **2** generation (Long coated conductors - electronics)	Ceramic $YBa_2Cu_3O_{7-d}$ ~90 K	Liquid nitrogen at 77 К and below (with other cryogens)	About 300-500$ @ 77К About 80-150$ @ 20К
Magnesium diboride - (Powder in tube – metallurgy)	MgB_2 – compound ~39 K	Liquid hydrogen and below (with other cryogens)	About 5$ @ 20 К

Magnesium diboride: now available, has high parameters (overall current density about $2\text{-}7 \cdot 10^4$ A/cm^2 at LH_2 temperatures) and most important:

pretty cheap!

Superconducting cable

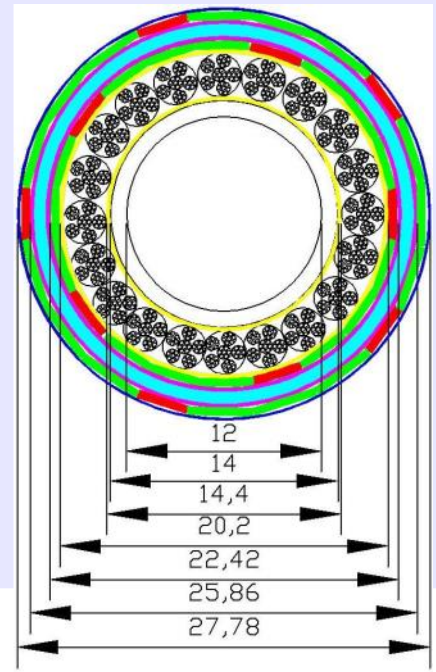


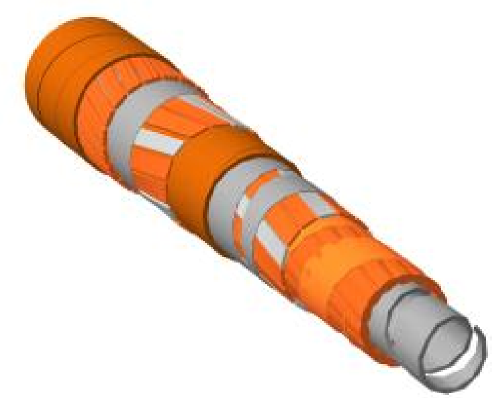
<u>Basic tape:</u> 3.65мм x0.65 мм MgB_2, Fe barrier, Ni matrix, Cu stabilizer

Produced by Columbus superconductor , Genova, Italy

Estimated: I_c (20 К, s.f.) ~520-540 A

Later measured: I_c(20K, s.f.)=529 A



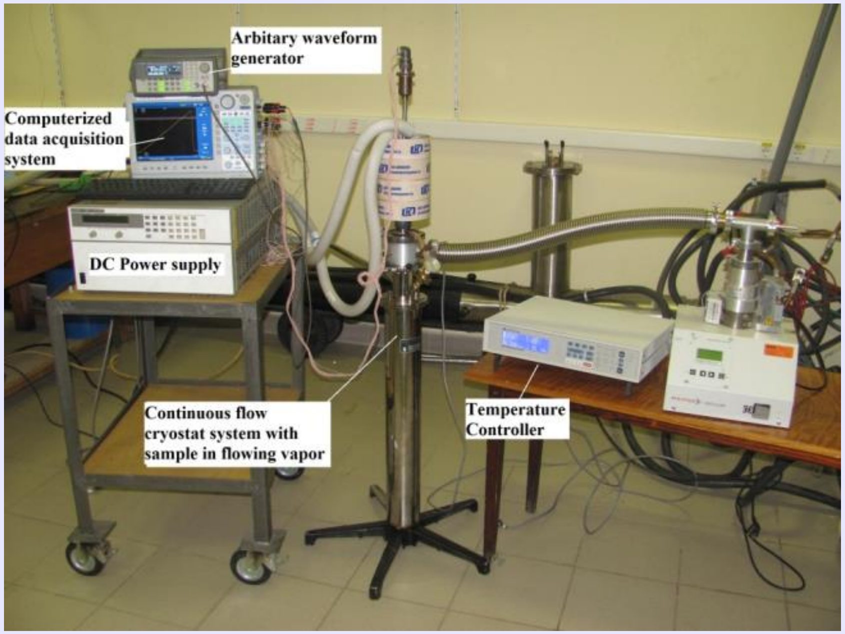


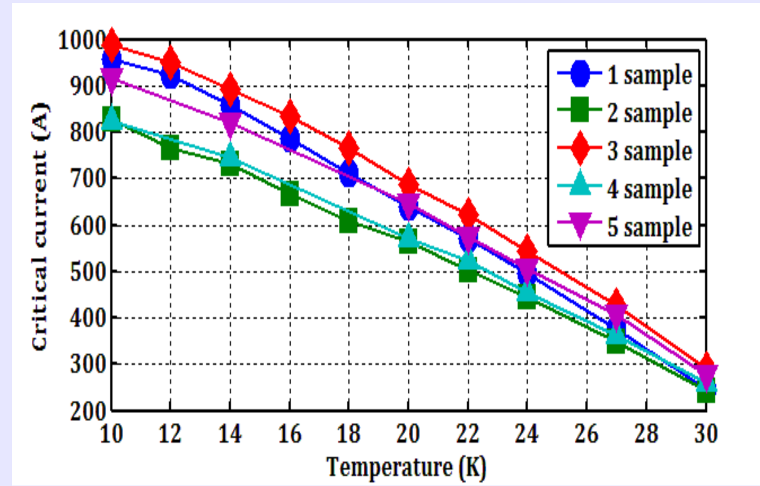
Cable: five tapes, two layers, total length 10 м, copper stabilization ~90 мм^2 for each layer

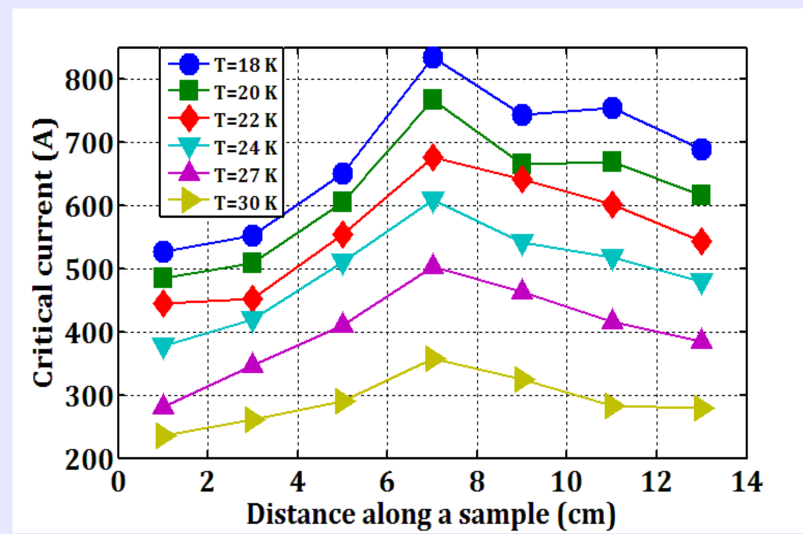
Insulation – 10 layers of Kapton, δ~1 мм, estimated as enough for 20-40 кV

Superconducting cable

short MgB2 samples tested

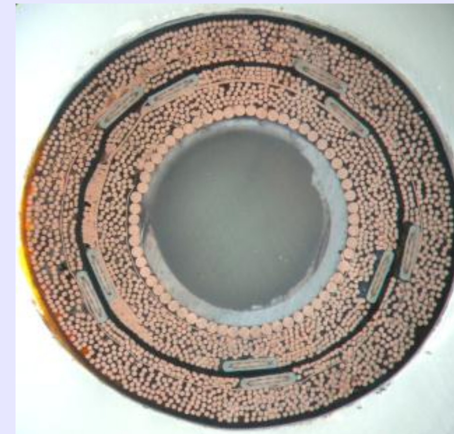


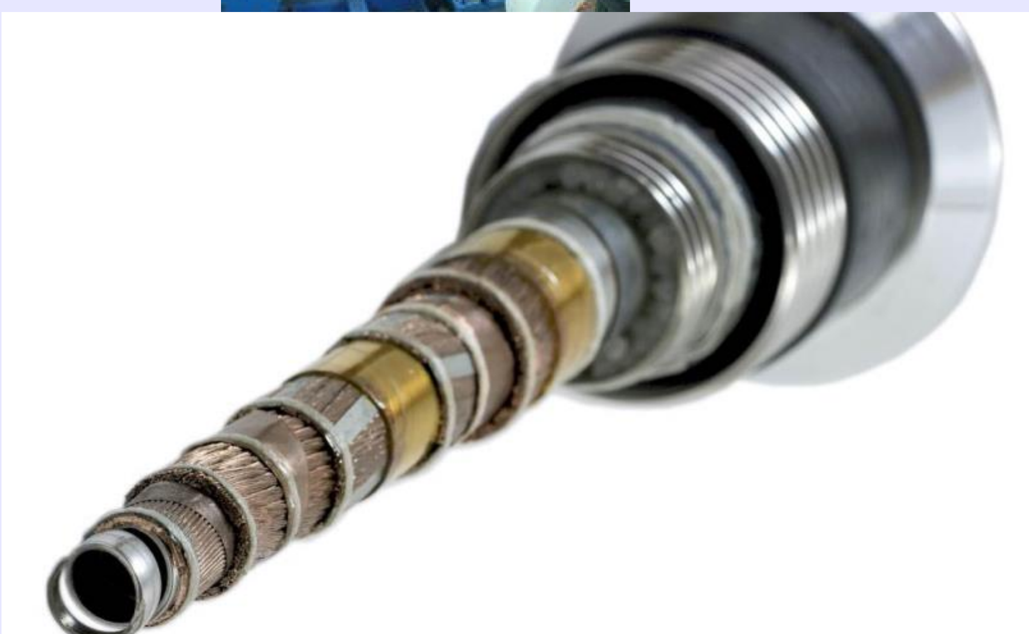




I_c non-uniformity has been observed but results in wires are better than specifications from Columbus Superconductor.
Paper 2MPC-11 at ASC-2012

Superconducting cable





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

Cryogenics test results were presented before at ICEC-24

Total cooling time ~380 s.

To cool the system it was used ~ 2.3 kg of LH_2.

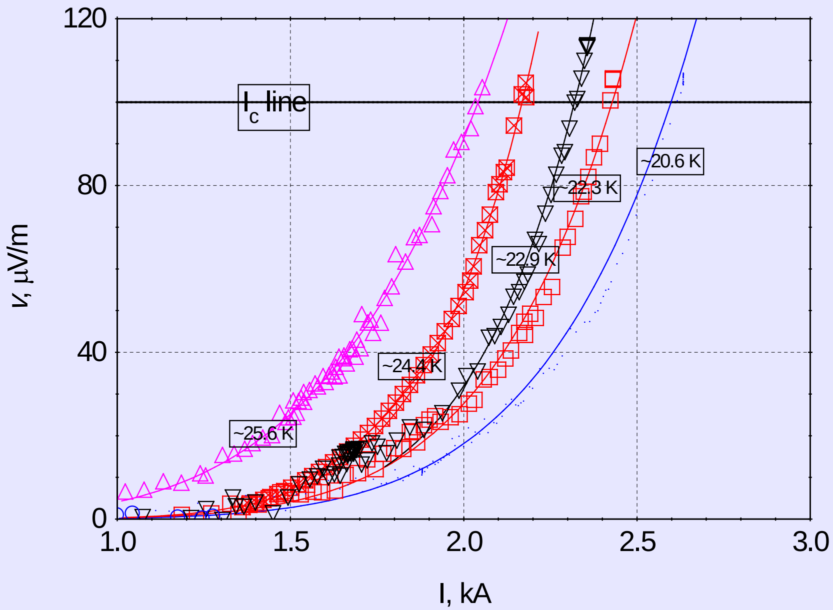
Estimated heat losses were below 10±2 W/m (good for LH_2), current lead losses at 2600 A~300 W.

Temperature at measurements were form 20 К 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

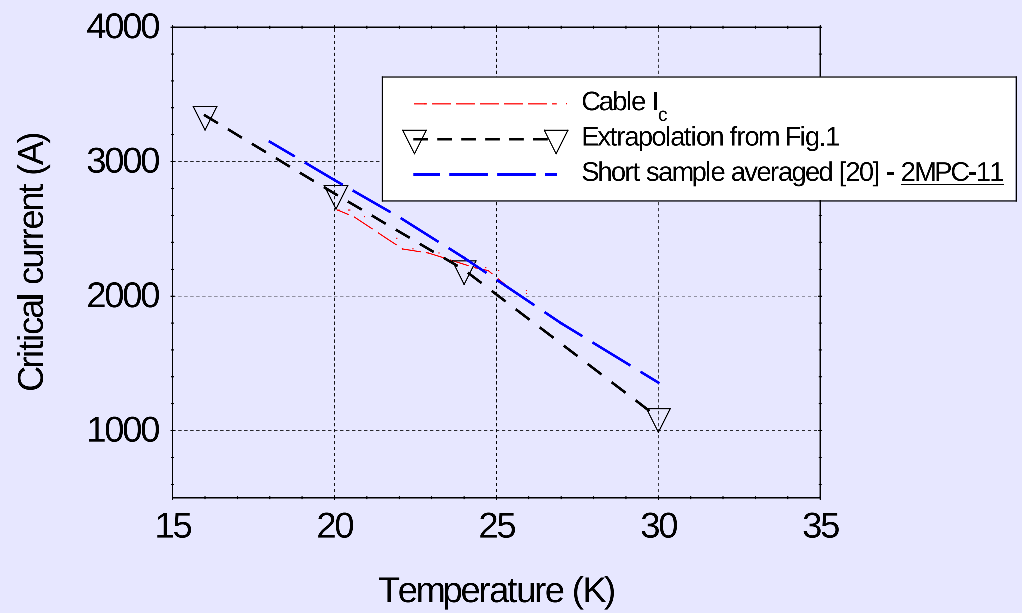
LH2 flow from 10 g/s to 250 g/s.

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.



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.

HYDRICITY CONCLUSIONS - II

First in the world <u>experimental prototype</u> 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 <u>flexible</u> 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

JSC "VNIIKP" – CONCLUSIONS

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! ☺

JSC “VNIIKP” – CONTACT

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MgB2 from Grid Logic