Development of low resistance splicing between Nb_3Sn and NbTi wires to make superconducting wigglers of Nb_3Sn superconductor

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MT-25 Conference,
August 29, 2017

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Parameters of SC wigglers and undulators

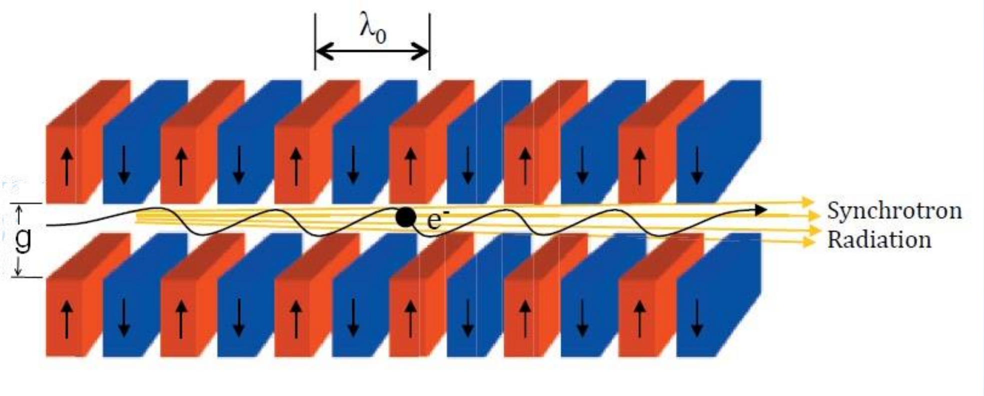
Main parameters of insertion devices are K parameter

$K = 0.93*\lambda_0[cm]*B[T]$

K~1 – undulator, K >>1 – wiggler

Magnetic field peak on the beam

$\tilde{B} = B_o / \cosh(\pi \, g/\lambda_0)$ depends on gap period.



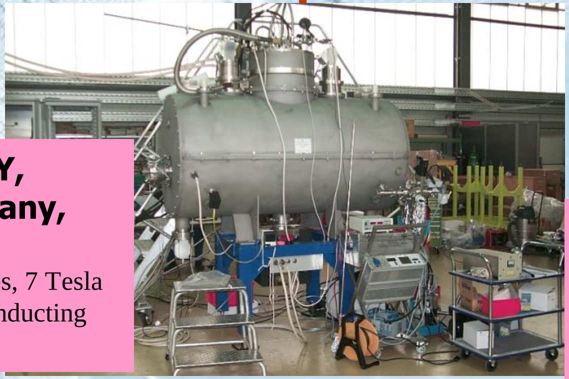
	Year	Magnetic field, T (Max)/normal	Poles number (main + side)	Pole gap, mm	Period mm	Vertical aperture, mm
7 Tesla wiggler (BESSY-II, Germany)	2002	(7.67)/ 7	13+4	19	148	13
3.5 Tesla wiggler ELETTRA (Italy)	2002	(3.7)/ 3.5	45+4	16.5	64	11
2 Tesla wiggler CLS (Canada)	2005	(2.2)/2	61+2	13.5	34	9.5
3.5 Tesla wiggler DLS (England)	2006	(3.75)/3.5	45+4	16.5	60	10
7.5 Tesla wiggler SIBERIA-2 (Russia)	2007	(7.7)/7.5	19+2	19	164	14
4.2 Tesla wiggler CLS (Canada)	2007	(4.34)/4.2	25+2	14.5	48	10
4.2 Tesla wiggler DLS (England)	2009	(4.25)/4.2	45+4	13.8	48	10
4.1 Tesla wiggler LNLS (Brazil)	2009	(4.19) /4.1	31+4	18.4	60	14
2.1 Tesla wiggler ALBA-CELLS (Spain)	2011	(2.28) / 2.1	117+2	12.6	30.0	8.5
4.2 Tesla wiggler Australian Synchrotron	2012	(4.5)/4.2	59+4	15.2	50.6	10
7.5 Tesla wiggler for LSU CAMD, USA	2013	(7.7)/7.5	11+4	25.2	200	15
2.5 Tesla wiggler for ANKA, Germany	2013	(2.85)/2.5	36+4	19	48	15

BINP experience in insertion device development

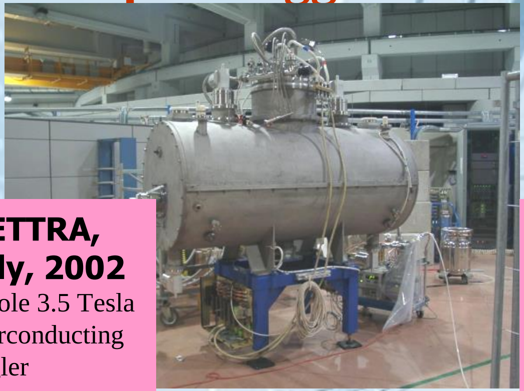
- BINP superconducting wigglers
- First wiggler was made in 1979

- 2005 – 2 Tesla 63 pole SCW for CLS, Canada
- 2006 – 3.5 Tesla 49 pole for DLS, England
- 2006 – 7.5 Tesla 21 pole SCW for Siberia-2, Moscow
- 2007 – 4.2 Tesla 27 pole SCW for CLS, Canada
- 2009 – 4.2 Tesla 49 pole SCW for DLS, England
- 2009 – 4.1 Tesla 35 pole SCW for LNLS, Brasil
- 2011 - 2.1 Tesla 119 pole SCW for ALBA, Spain
- 2012 - 4.2 Tesla 63 pole SCW for Australian Synchrotron
- 2013 – 7.5 Tesla 15 pole SCW for Louisiana St. University, USA
- 2013 – cryostat upgrade for 3.5 Tesla SCW ELETTRA, Italy
- 2013 – cryostat upgrade for 7 Tesla SCW for HZB (BESSY), Germany
- 2013 – 2.5 Tesla 44 pole SCW for ANKA, Germany
- 2015 – 3 Tesla 68 pole SCW for ANKA-CLIC, Germany and CERN
- 2018 – two wigglers will be manufactured for Dortmund and Moscow
- 2019 – one wiggler will be manufactured for Moscow SR center
- two insertion devices will be made for RRCAT, India (the contracts not signed yet)

Superconducting multipole wigglers

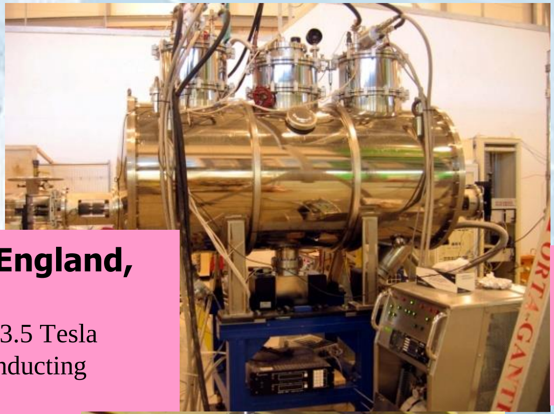


BESSY, Germany, 2002
17-poles, 7 Tesla superconducting wiggler

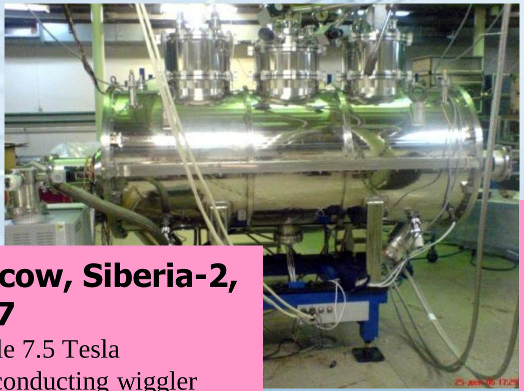


ELETTRA, Italy, 2002
49-pole 3.5 Tesla superconducting wiggler

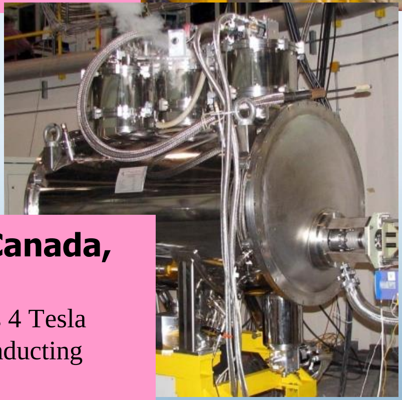
CLS, Canada, 2004
63-pole 2 Tesla superconducting wiggler



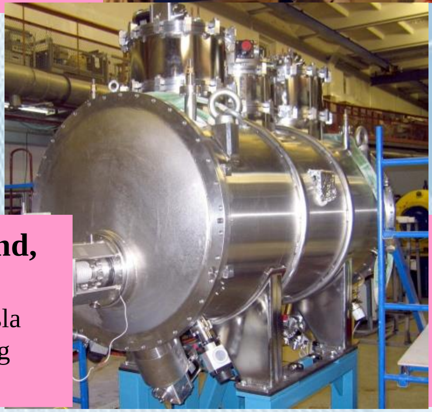
DLS, England, 2006
49-pole 3.5 Tesla superconducting wiggler



Moscow, Siberia-2, 2007
21-pole 7.5 Tesla superconducting wiggler

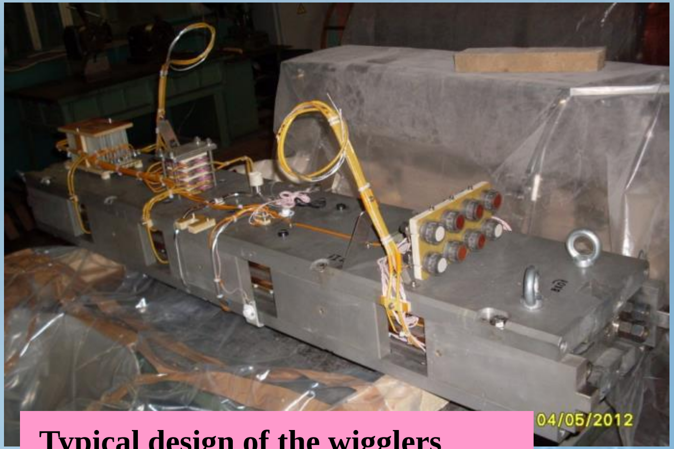


CLS, Canada, 2007
27- poles 4 Tesla Superconducting wiggler



DLS, England, 2008
49-pole 4.2 Tesla superconducting wiggler

LNLS, Brazil, 2009
35-pole 4.2 Tesla superconducting wiggler



Typical design of the wigglers

Horizontal racetrack design of BINP devices. High parameters.

The design of the BINP devices has the following features

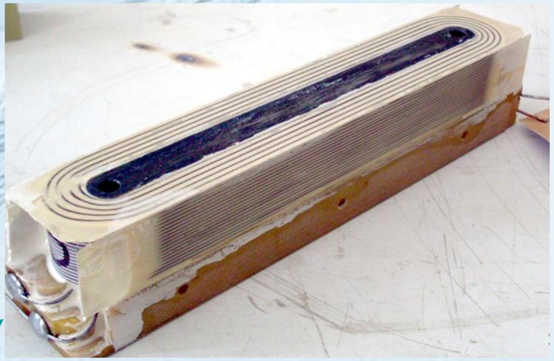
- the coils are separately made of a race-track shape

- most of them are wet wound with epoxy compound. High thermal capacity powders such as Gd_2SO_3 were added.

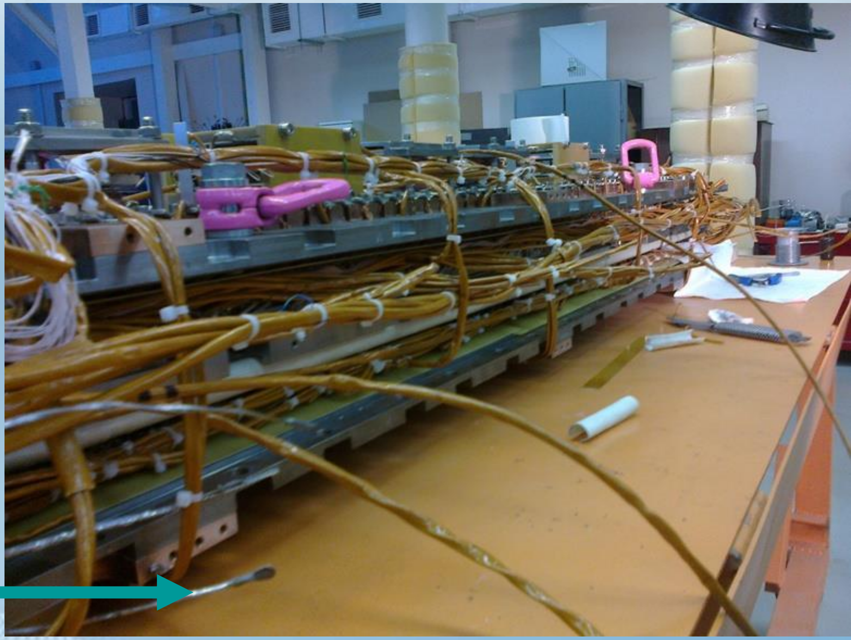
- the coils are charged by graded current

- NbTi wires of Cu/ NbTi ratio as low as 1/2. Such wires were manufactured in Bochvar Inst. on specific order from BINP.

- low resistivity joints of the coils terminals based on Ar arc welding. The resistance of the welded terminals is below 10^{-12} Ohm. The number of such splicing in one wiggler can be more than 200 at operating current ~ 1 kA. That is important if cryocoolers are operating without LHe boil-off.



this coil has four terminals



Task of this work

The today Nb_3Sn wires has two-three times more J in low B than of NbTi wires. So, the next generation of the insertion devices would be made of the Nb_3Sn superconductor. Existing examples of such magnets have limited amount of splicing and does not have very low resistance splicing.

The design of the magnets is considered to be the same as of currently made BINP magnets with horizontal race-track coils which are separately made and easily changed.

The terminals of Nb_3Sn coils should be spliced with NbTi wires with low resistance. During the magnet assembling the coils will be connected via NbTi wires by existing technology.

The splicing will be placed in low magnetic field region of the magnet structure.

The main idea of the current work is presented on this picture.

Low resistance means that the splicing resistance is < 10^{-10} Ohm for wires having diameters less than 1 mm.

The real design will be more complicated.

Technology of Nb_3Sn-NbTi splicing

The technology steps of the splicing are:

A. Etching the terminals to release the Nb and NbTi filaments.

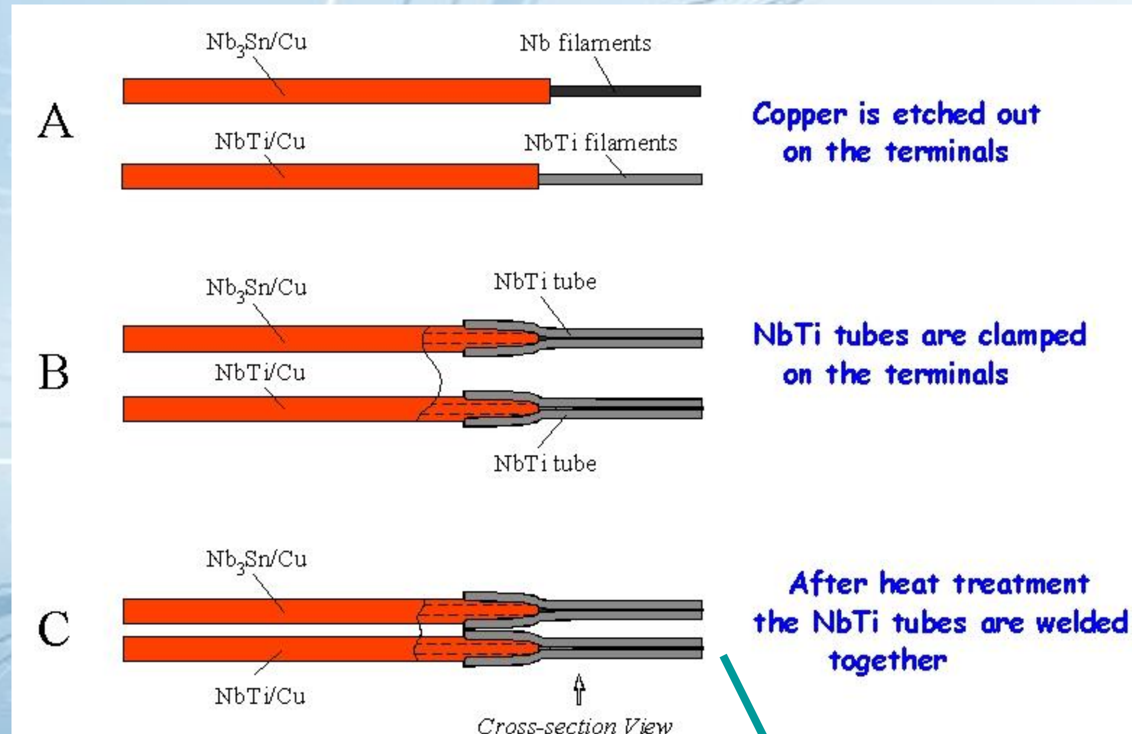
Acids were used: HNO_3 for copper etching and HNO_3+HF for Ta tube etching in the Nb_3Sn wire.

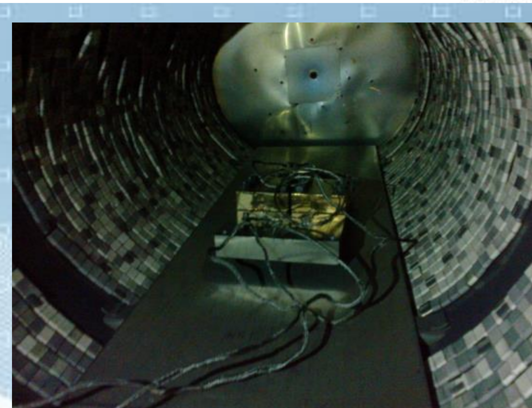
B. Tubes of NbTi alloy were clamped on the etched terminals.

Oxide layers on the tubes and the filaments were etched out by HNO_3+HF dilution.

C. The Nb_3Sn wire is heat treated according a prescribed procedure for this wire.

The terminals are welded by arc welding with Ar gas.





Heat treatment of the Nb3Sn wires

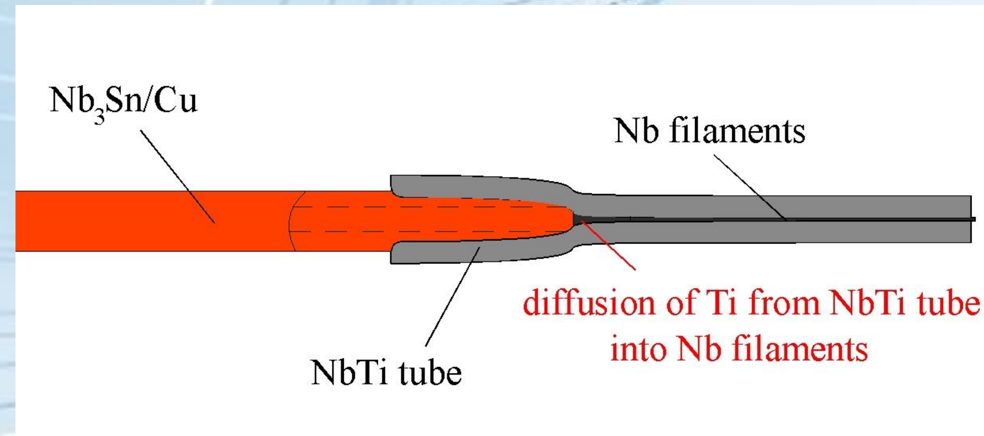
The view of the splicing

Why low resistance of Nb_3Sn-NbTi splicing can be achieved

In some papers information about Nb3Sn-NbTi splicing can be found. The results were not promising there.

The technology described above is based on Ti diffusion from NbTi tubes into Nb filaments of Nb3Sn wire.

Diffusion of Ti into Nb can be estimated according $L = 2\sqrt{D \cdot t}$ it gets ~ 1 μm



The cross-section of the wire terminal is shown above.

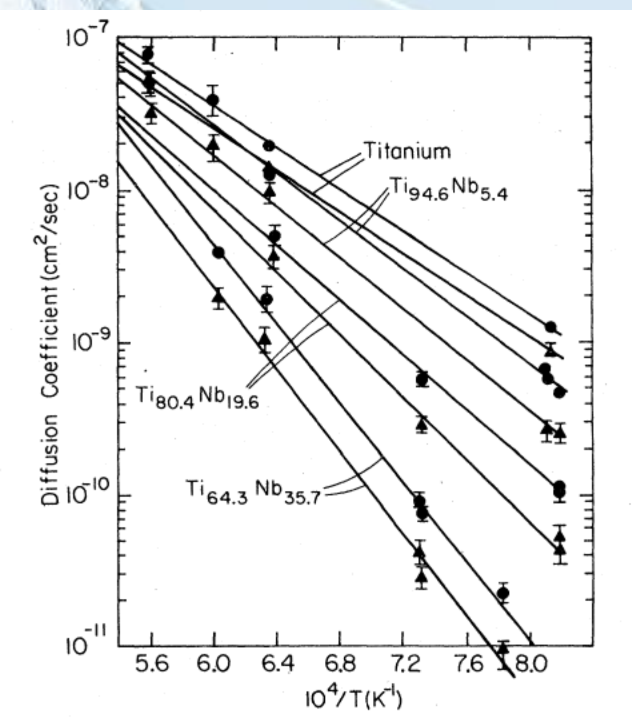


FIG. 3. Measured diffusion coefficients of titanium (circles) and niobium (triangles) in Ti, $Ti_{94.6}Nb_{5.4}$, $Ti_{80.4}Nb_{19.6}$, and $Ti_{35.7}Nb_{64.3}$ as a function of temperature.

Basic information from books and papers.

2% of Ti in Nb3Sn increases its critical magnetic field;

Nb itself has 0.4 T of critical field

$Nb_{0.9}Ti_{0.1}$ alloy has 3.5 T of the critical magnetic field.

Сплав	x	T_c, К	$H_{c2}(0)$, Тл	θ_D, К	γ, мДж/(моль·К²)	λ
$Nb_{1-x}Ti_x$	0,1	9,61	3,5	—	—	—
	0,25	10,0	9,05	—	—	—
	0,45	9,4	10,8 *	—	—	—
	0,78	7,5	7,7 *	—	—	—
$Nb_{1-x}Zr_x$	0,50	9,3	9,2	238	8,3	0,88
	0,25	10,6	8,2	246	8,9	0,93
$Nb_{1-x}Mo_x$	0,15	5,85	—	265	6,3	0,70

The samples design and resistance measurements

The test samples are two turns loops made of Nb3Sn and NbTi wires spliced together.

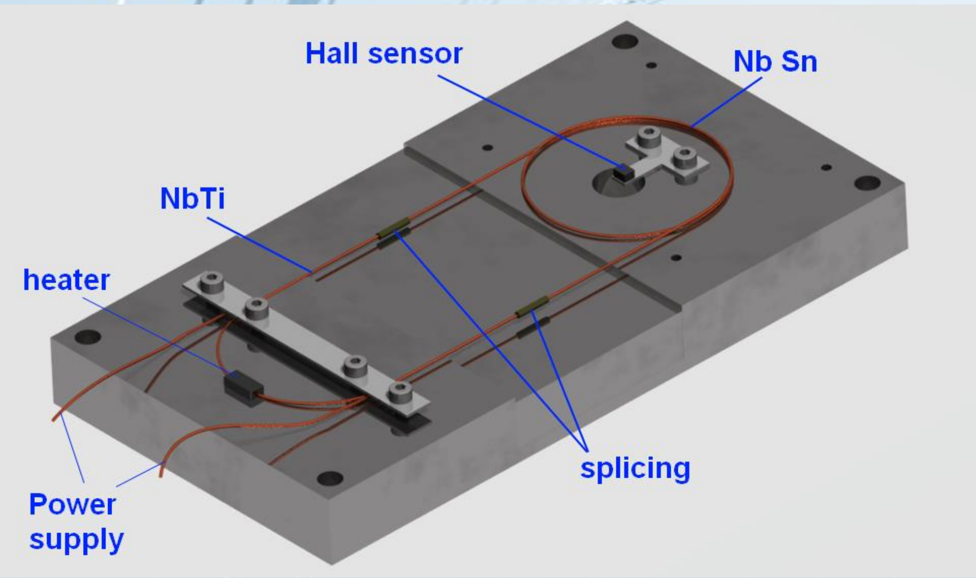
There are two splices per sample.

The measured values are:

-Hall sensor voltage

-PS current

-Three thermal sensors: on the sample, heater, cryocooler 2-nd stage.



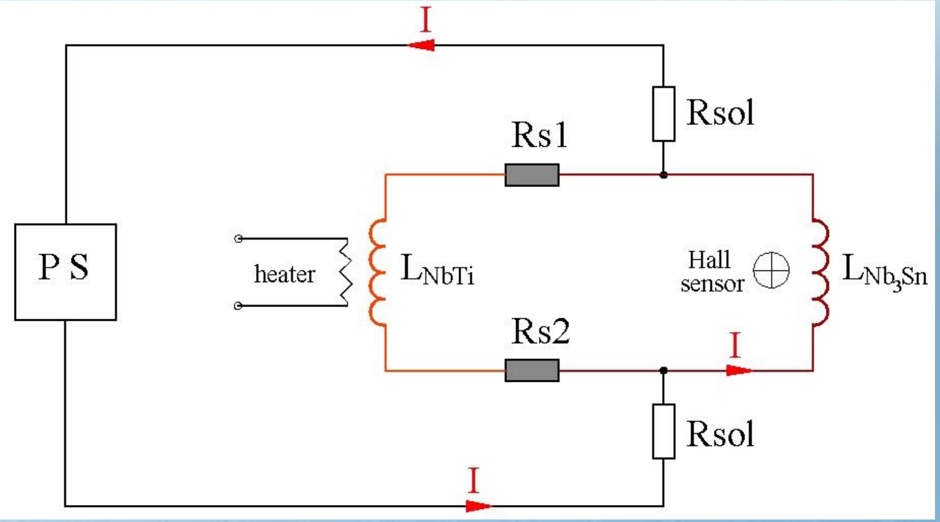
Procedure of the sample tests

-the current was risen in the cold sample; it goes mostly via L_{NbTi}

-the heater is switched on, the current goes via L_{Nb_3Sn}, Hall sensor value is recorded as reference on residual current in the sample

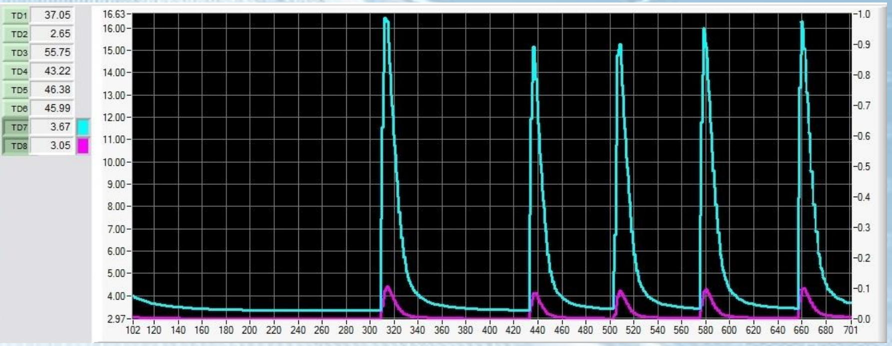
-the current is ramped down

-residual current decay is registered



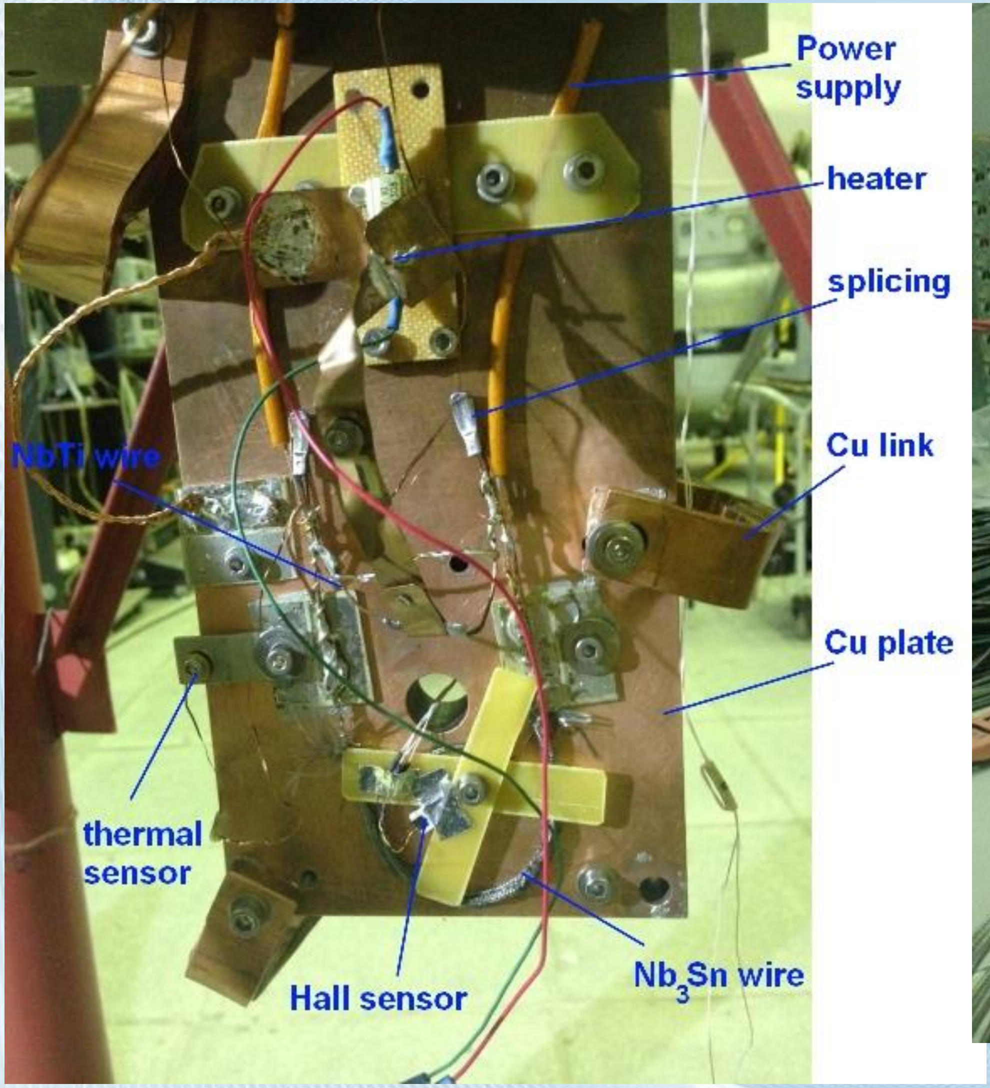
Electrical scheme of the sample

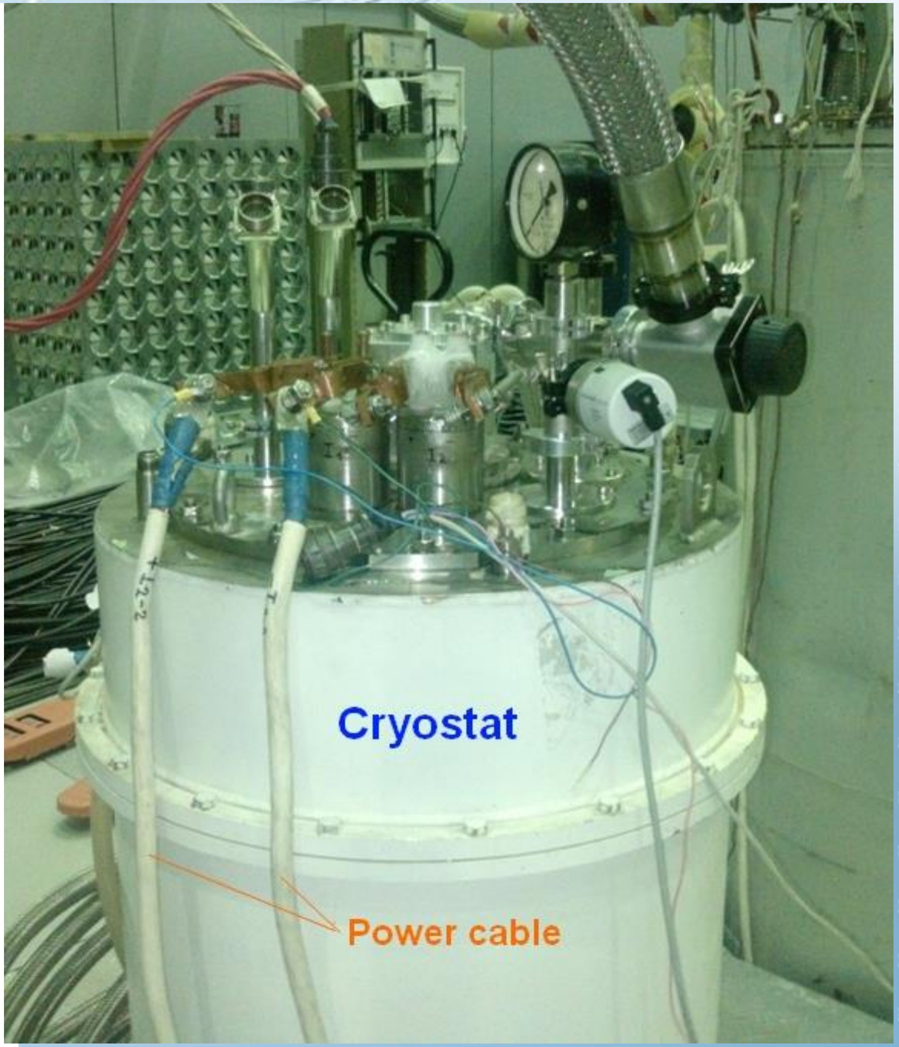
The voltmeter is HP 34401A.



Temperature sensors during the first current ramping. The stops were at 50 A, 100 A, ...

The Nb_3Sn-NbTi samples and the cryostat





The cryostat is dry. The sample is cooled by the cryocooler's 2nd stage via copper links.

Results of the tests

1. Five properly made samples were tested, the result is shown in the table below

Sample No	U_H, μV	I, A	L, 10^{-7} H	t, s (days)	R, Ohm
1	147	227	6.7	1123200 (13)	$< 2.0 \cdot 10^{-15}$
2	364	287	6.0	244800 (2.8)	$< 3.4 \cdot 10^{-15}$
3	148	251	6.0	86400 (1.0)	$< 2.4 \cdot 10^{-14}$
4	330	388	6.0	345600 (4.0)	$< 2.2 \cdot 10^{-15}$
5	446	432	6.0	604800 (7)	$< 1.1 \cdot 10^{-15}$

No current decay in these samples was registered.

The resistance was estimated according

$$R = -\frac{L}{2 \cdot t} \ln\left(\frac{U^*}{U_H}\right)$$

where $U^* = U_H - 1$ μV was taken.

2. Two obviously broken samples had shown current decay with resistance ~ 10 nOhm.

3. Highest residual circulating current was about 500 A.

4. The current increase from sample to sample, except for No 3, is shown. It is caused by improvements made for samples cooling and decreasing the resistance of soldering connections between the samples and power wires.

Discussion of the results and further actions

1. The main result is that new technology of splicing the NbTi and Nb_3Sn superconductors was demonstrated.

2. The achieved resistance in the tested samples is much lower than needed. For the splicing the superconducting coils at ~ 1.5 kA operating current it is enough to have ~ 10^{-10} Ohm of splicing resistance.

3. The achieved current in the samples is lower than will be in the Nb_3Sn wigglers and undulators. Further work will be aimed to increase the current in the samples and to making Nb_3Sn coils with NbTi wire terminals.

4. The proposed design of Nb_3Sn horizontal race-track coils can be used in:

- CLIC project wigglers, it needs 104 wigglers for damping rings, high magnetic field and ~ 2 m of length
- superconducting undulators of short period.

THANK YOU!