Examples of International Cooperation on Superconducting Magnets R & D in High Energy Physics

H. Hirabayashi

KEK National Laboratory for High Energy Physics
Oho-machi, Tsukuba-gun, Ibaraki-ken, Japan 305

Introduction

There are several cases of international cooperation in the field of superconducting magnet technology in high energy physics. For instance we know the Saclay-Serpukhov cooperation on the accelerator magnet development and the cooperative work on magnets between CERN and European countries.

In general, international cooperation is useful for mutual information exchange on topics, efficient utilization of manpower and experimental facilities, and competitive development among the countries or regions.

In this report three examples of the Japan-US cooperation on superconducting magnet R & D in high energy physics are briefly described together with their extended developments in Japan.

1. NbTi alloy superconducting magnets

In cooperation with Fermilab and NRIM (National Research Institute for Metal, Japan), KEK has made a series of basic studies on binary and ternary alloy superconducting wires for high field magnets.[1)]

KEK and NRIM made many short samples of binary and ternary wires and tested them up to 12 T at 1.8 K. They were also tested several times at the Fermilab with the participation of KEK physicists.

Figure 1 shows the critical current densities versus magnetic fields of various binary and ternary alloy superconducting wires. The ternary alloy wire of NbTiTa has the largest current density at 10 T and 1.8 K, but the increment in its current density is not so much compared with that of the binary NbTi wire. Nevertheless, the present cost of the ternary NbTiTa wire is three times as expensive as that of the binary NbTi wire.

On the basis of these data, KEK is now developing 10-T window-frame NbTi/Cu dipole magnet with a cooling bath of pressurized helium II.[2] This dipole has a coil length of 1 m and an aperture of 60 mm. Its coils are basically wound in a race-track shape. Both ends of the median plane coils are bent up or down to clear the beam space (see Fig. 2). The coils are cured under a pressure over 60 MPa and tightly clamped with laminated collars. The main design parameters of this dipole are given in Table 1.

In this type of dipoles, the largest stress is caused by the bursting force in the horizontal direction, which is estimated to be 6.2×10^6 N/m at full excitation. The maximum stress in this coil is expected to be 108 MPa. This value is so large that only a special composition of superconductor and insulator can survive.

At first we designed and constructed the dipole coils with NbTi/Cu monolithic cable. After several testing at 4.2 K and 1.8 K, we found that the cable can not carry a sufficient current for a 10 T dipole. A large increment in the critical current of the cable at 1.8 K, compared with that at 4.2 K, could not be attained. This might be attributed to the shortage of flux pinning force in the cable caused by the insufficient cold working on the superconductors.

Now we are producing a series of window frame coils with high current NbTi/Cu compacted strands cables. Each strand consist of 2,000 fine NbTi filaments, twisted and embedded in a copper matrix. The strands are compacted in a rectangular cross section cable. The cable of 27 strands can carry 6.9 kA at 10 T and 1.8 K. The operating current is estimated to be 90% of the critical current.

A special cryostat is also prepared, for cooling the collared NbTi/Cu window frame coils below 2 K by pressurized helium II. Two laminated iron yokes surround the collared coils. The inner yoke is cooled with liquid helium at 4.5 K, while the outer one is cooled with liquid nitrogen at 77 K.

This window frame dipole is a trial superconducting magnet for high field accelerators. The basic problems on the NbTi/Cu dipole, cooled with pressurized helium II, will be studied in detail in comparison with the results of the double shell dipole magnets at KEK.[3]

2. Nb_3Sn Superconducting magnets

Since 1981 KEK and BNL have carried out the cooperative studies on the basic properties of Nb_3Sn superconducting wires and cables such as the stability, critical current density, etc.[4)]

For example the influence of stabilizing copper on the quench characteristics of Nb_3Sn/Cu wire was studied in detail. For high field accelerator magnets, high current densities in the coils (several hundreds A/mm^2) are required to make them reasonably small. This can be attained by increasing the current density within the superconductor (Nb_3Sn) and minimizing the copper stabilizer. In past several years there have been substantial industrial developments on Nb_3Sn multifilamentary wires: at present wires with very high current densities, more than 1,000 A/mm^2 at 10 T within the superconductor, are commercially available. However, few studies have been made on the electromagnetic stability of these Nb_3Sn/Cu wires, and it is not clear how much copper is required for stabilization of the conductor for these magnets. An investigation has been carried out on the influence of the amount of stabilizing copper in a Nb_3Sn/Cu wire on the quench energies and quench propagation velocities at high magnetic fields.

This study has been made at BNL with the participation of a KEK physicist. The conclusions are as follows. Measurements of the minimum energy to quench Nb_3Sn/Cu wires show that 40% copper is optimum for stabilizing the wire (see Fig. 3). In the case of good cooling the minimum quench energy for the Nb_3Sn/Cu wire at 10 T is almost the same as that for the NbTi/Cu wire at 5 T. However, in the case of poor cooling the energy to quench the Nb_3Sn/Cu wire is approximately a factor of 3 as great as the energy to quench the NbTi/Cu wire. There is a clear correlation between the MQE (minimum quench energy) and the quench propagation velocity of the specimen: the wire whose MQE is large has a low propagation velocity. The propagation velocity of 40%-Cu specimen at 10 T is almost the same order of magnitude as that of NbTi/Cu wire at 5 T, if we compared them at a constant overall current density.

Besides these basic cooperative studies, KEK has developed two kinds of Nb_3Sn/Cu dipole magnets. As the first step, a single layer race-track dipole magnet has been made with a high current monolithic cable.[5)] The parameters of the magnet and cable are given in Table 2. The magnet structure is shown in Fig. 4.

This race-track dipole was made to study the production technique of a real size dipole with the "wind and react" method. The Nb_3Sn/Cu cable was insulated by synthetic Mica glass tape and wound in a race-track coil. Before the heat treatment, the wound coil was placed in a strong jig. After the heat treatment for 48 h at 720°C in inert gas, the Nb_3Sn superconductor was produced in the copper stabilizer. The jig was disassembled to check the insulation and coil dimensions. The insulator could withstand for the hard heat treatment; no defect in the insulator was found., Longitudinal elongation of the cable and coil of the order of 0.5% were observed. This elongation should be taken into account in a long Nb_3Sn dipole produced by the "wind and react" method. After adding two pieces of Mica sheets to the upper and lower surfaces of the coil layer, the magnet was reassembled in the magnetic iron plates without impregnation of epoxy resin.

This race-track dipole magnet was successfully operated to the upper limit current of the power supply with two quenches. The minimum quench energy, the normal zone propagation velocity and other properties were measured.

As the second step, KEK is now developing twofold and threefold double shell dipoles. In these magnets, the dipole fields are generated by two or three pairs of double shell coils. Each pair of coil shells generates a dipole field in the center of the aperture and the Nb_3Sn/Cu cables are graded depending on the magnetic fields.

The total ampere-turns required for 10 T dipole field are approximately 1 MAT and the stored energy is nearly 1 MJ/m. There is a huge bursting force of about 7 MN/m. The maximum stress in the coils is calculated as 150 MPa at 10 T. In such huge stress, any kind of organic insulators can not survive. This is one of the reasons why we are studying the inorganic insulators for the Nb_3Sn/Cu dipoles.

Although these shell dipoles are studied with monolithic Nb_3Sn/Cu cables at present, the monolithic cables could be replaced with the compacted strands cables in the future, if the excellent reinforced cables become available. Figure 5 shows the schematic half cross section of the twofold double shell dipole.

3. Superconducting thin solenoid using aluminum-stabilized conductor

Prior to the construction of the CDF solenoid now being built by Tsukuba University and Fermilab for the $\bar{p}p$ colliding beam experiment at Tevatron, a prototype superconducting thin solenoid of 1 m^{ϕ} × 1 m^{ℓ} was developed by a joint group of KEK and Tsukuba University.[6)] This development was also made as a task of the Japan-US cooperation in high energy physics. Table 3 summarizes the parameters of the magnet.

One of the most important issues in this development was the successful industrial production of an excellent aluminum-stabilized superconductor. The superconductor, used in this prototype solenoid, was produced by a special technique of Hitachi Ltd. The NbTi/Cu superconducting wire was embedded in a aluminum strip with a metallurgical bond.

The schematic diagram of the conductor cross section is shown in Fig. 6. The volume ratio of Aℓ:Cu:NbTi is 24:1:1. The NbTi/Cu composite consists of 1,400, 50 μm^{ϕ} NbTi wires. The critical current is 7.7 kA at 2 T and 4.2 K. The binding between aluminum and copper was made with the friction welding method. The diffusion thickness of the two metals is about 1 μm when tested to give the maximum binding strength. Aluminum of high purity (99.99% purity and RRR > 1000) was used to provide better stability to the conductor during quenches.

In the excitation test of this solenoid, propagation velocities of the normal zone were measured as a function of the magnet excitation current. The normal zone propagated mainly in the direction of the conductor. The propagation in the axial direction through the coil insulations was negligible.

Measurements on resistivities of the conductor at various sections of the solenoid during quenches indicate that the conductor current spread promptly from the NbTi/Cu superconducting wire to the aluminum stabilizer immediately after the superconducting wire became normal. This means that the aluminum-stabilized superconductor, used in this solenoid, has very good electrical connection between the NbTi/Cu superconducting wire and aluminum stabilizer.

Resistive voltages in normal zones showed small and smooth rise after quenches. Therefore, the temperature of the conductor rose very slowly and smoothly and no abrupt local heating took place.

In conclusion the aluminum-stabilized superconductor of the prototype solenoid has excellent electrical and thermal properties which are required for thin and large superconducting solenoids.

After the successful development of this prototype solenoid, the aluminum-stabilized NbTi/Cu superconductor has become commercially available in Japan. Using this type of superconductor, Tsukuba University is now constructing the CDF solenoid at Tevatron in close cooperation with Fermilab.[7)]

Besides the CDF solenoid, two more solenoids with aluminum-stabilized NbTi/Cu conductors are now being built at KEK for the TOPAZ and VENUS detectors in the TRISTAN project.[8)]

4. Conclusion

Above examples show that present international cooperation on the superconducting accelerator magnets is limited to the basic R & D problems. On the other hand, it is widely recognized that the future hadron accelerators in multi-TeV region necessitate a large number of high quality superconducting magnets and huge cryogenic systems. These circumstances compel us to persue high degree international cooperation on superconducting technology; therefore, the style of the future cooperation on superconducting magnets should be changed. Possible scheme of international cooperation in the future magnet technology should be extensively studied.

So far as the detector magnets are concerned, we have already real experiences of the international cooperation. This kind of cooperation should be continued in the future.

References

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7) "Design report for an indirectry cooled 3-m diameter superconducting solenoid for the Fermilab collider detector facility", Fermilab, October (1982)

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KEK, TRISTAN-EXP-002 Proposal, TOPAZ Collaboration (1983)

Table 1. Main design parameters of window frame dipole and NbTi/Cu cable

Coil length	1.0 m
Central field	10 T
Peak field	11 T
Operating current	6.9 kA
Turns per pole	176
Coil current density	300 A/mm^2
Inductance	25 mH
Stored energy	615 kJ
Cable:	
Number of strands	27
Number of filaments per strand	2,000
NbTi filament diameter	13 μm
Superconductor to copper ratio	1 to 1
Current at 10 T and 1.8 K	6,970 A
Cross section of cable	1.67 × 12.35 mm^2
Packing factor	85%

Table 2. Parameters of Nb_3Sn/Cu race-track coil magnet

Coil:	
Inner width	25 mm
Outer width	181 mm
Thickness	6 mm
Length	956 mm
Length of coil straight section	800 mm
Number of turns	30
Insulation	Mica glass tape
Superconductor:	
Cross section	2.3×6.0 mm^2
Process	bronze
Filament diameter	5.3 μm
Number of filaments	121,220
Twist pitch	240 mm
Matrix	Cu-Sn (14.5 wt%)
Barrier	Nb
Copper fraction	35%
Critical current	11,700 A at 4.65 T, 4.2 K
(criterion 10^{-13} Ω·m)	4,600 A at 10 T, 4.2 K

Table 3. Parameters of prototype solenoid wound with aluminum-stabilized NbTi/Cu conductor

Coil:	
Inner diameter	978 mm
Outer diameter	1090 mm
Length	1140 mm
Number of turns	269
Number of joints	2
Inductance	48 mH
Resistance	320 mΩ at 290 K
	0.3 mΩ at 10 K
Superconductor:	
Cross section	20 mm × 3.59 mm
Material ratio Aℓ:Cu:NbTi	24:1:1
NbTi wires	1400 × 50 μm^{ϕ}
Design current	4.45 kA
Bobbin and banding material	A5083
Cooling	Indirect forced cooling

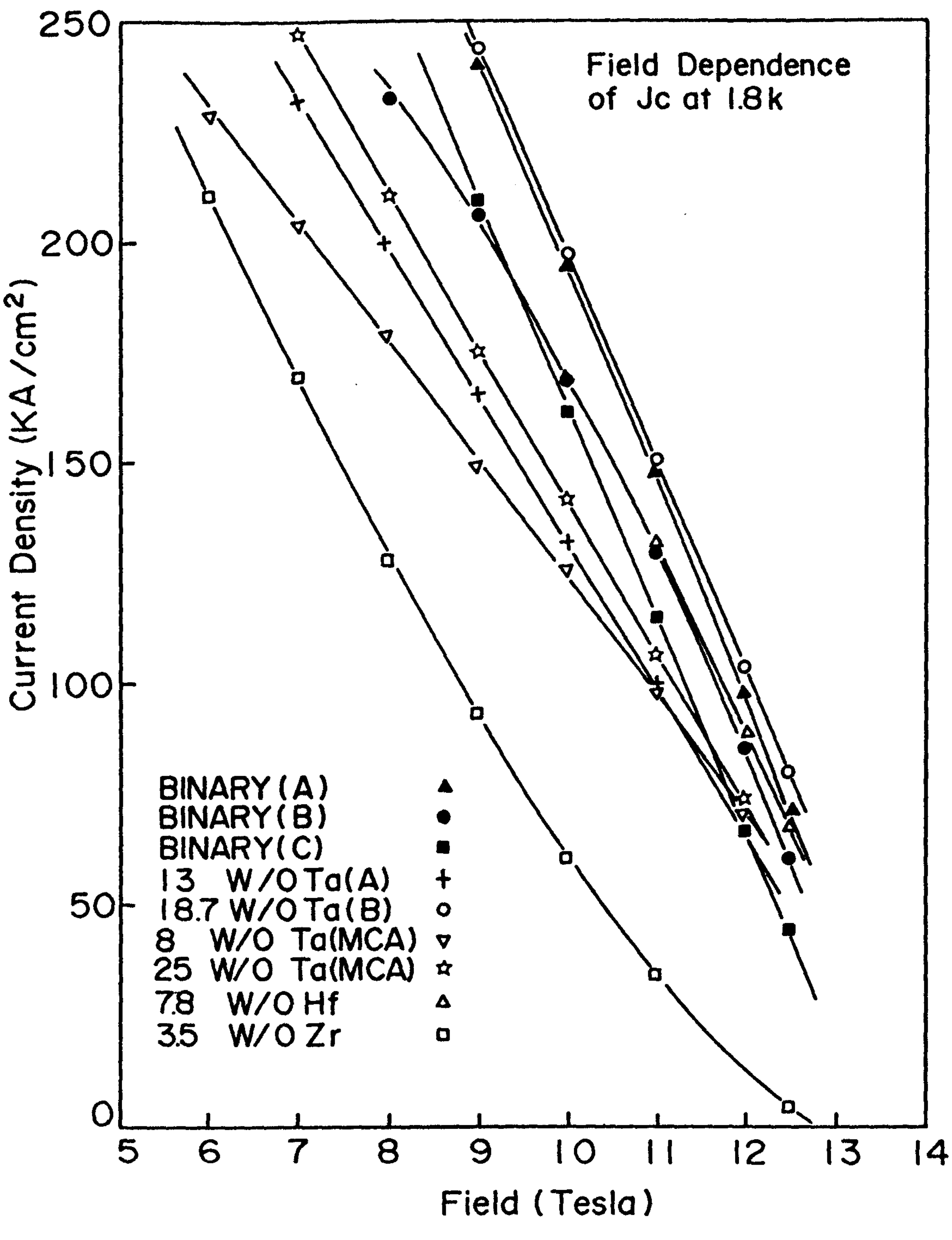

Figure 1. Critical current densities of binary and ternary alloy superconductors

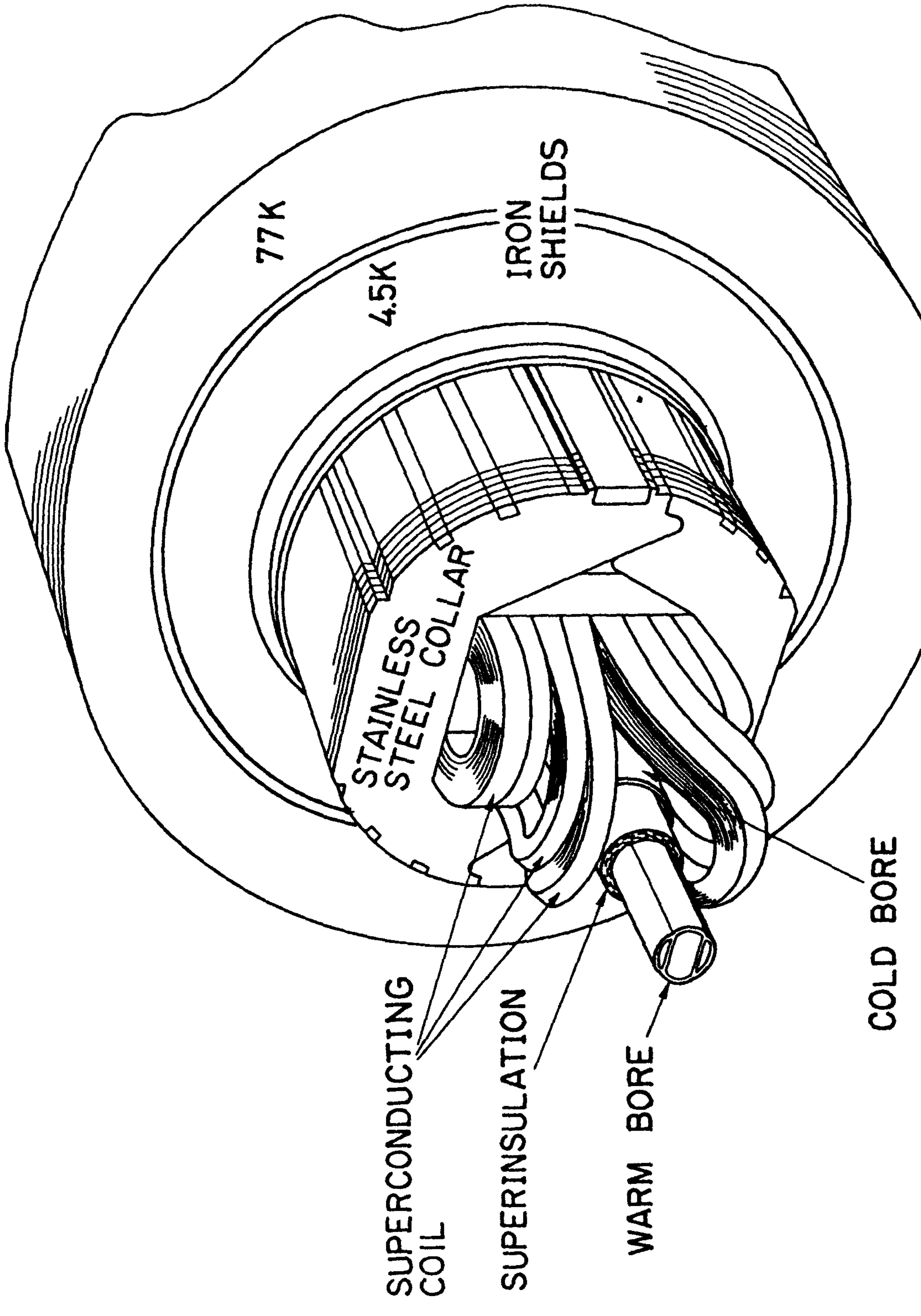

Figure 2. Structure of NbTi/Cu window frame dipole

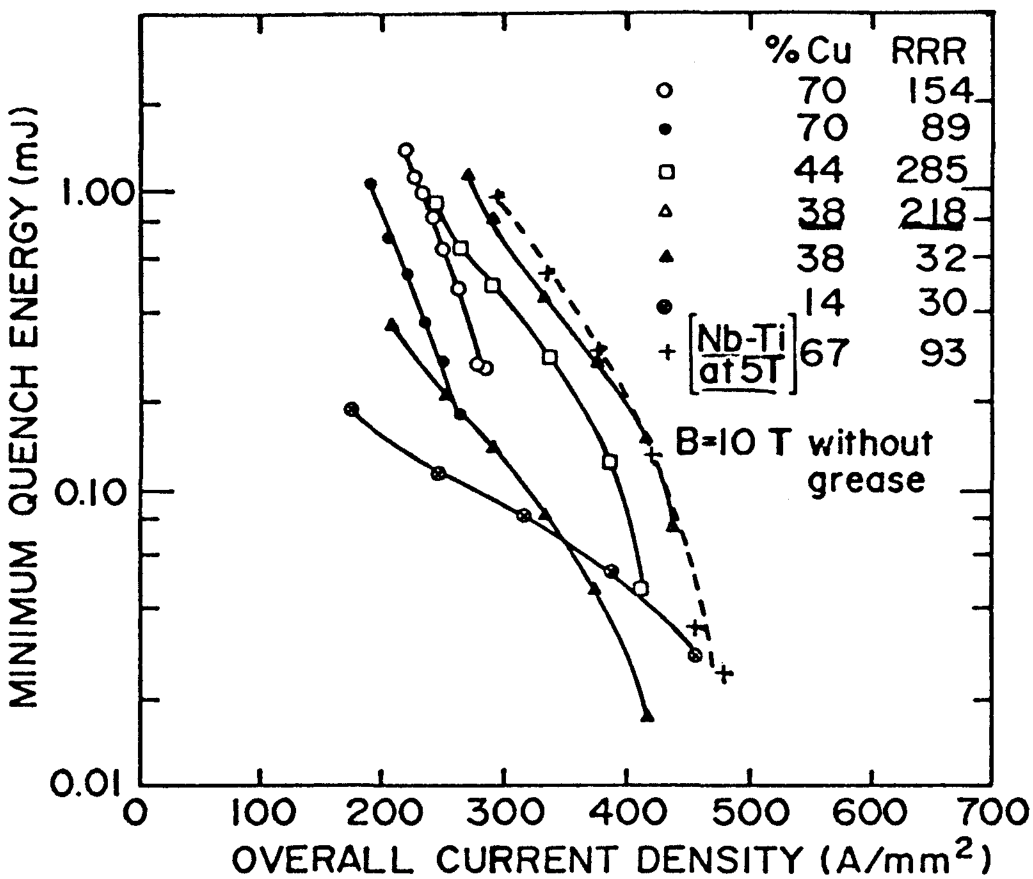

Figure 3. Minimum quench energy versus transport current density for Nb_3Sn wires in liquid helium

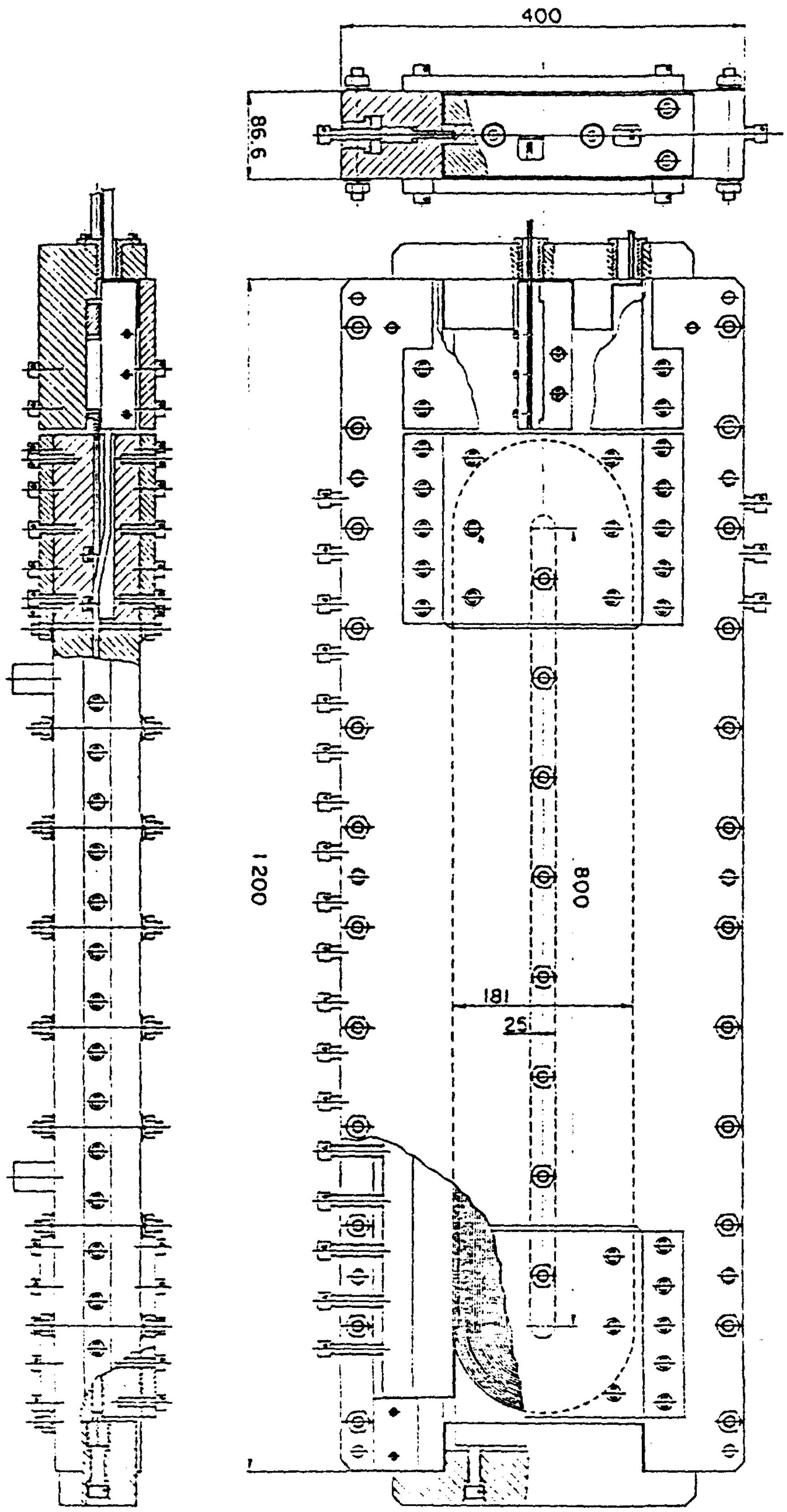

Figure 4. Structure of Nb_3Sn/Cu race-track coil magnet

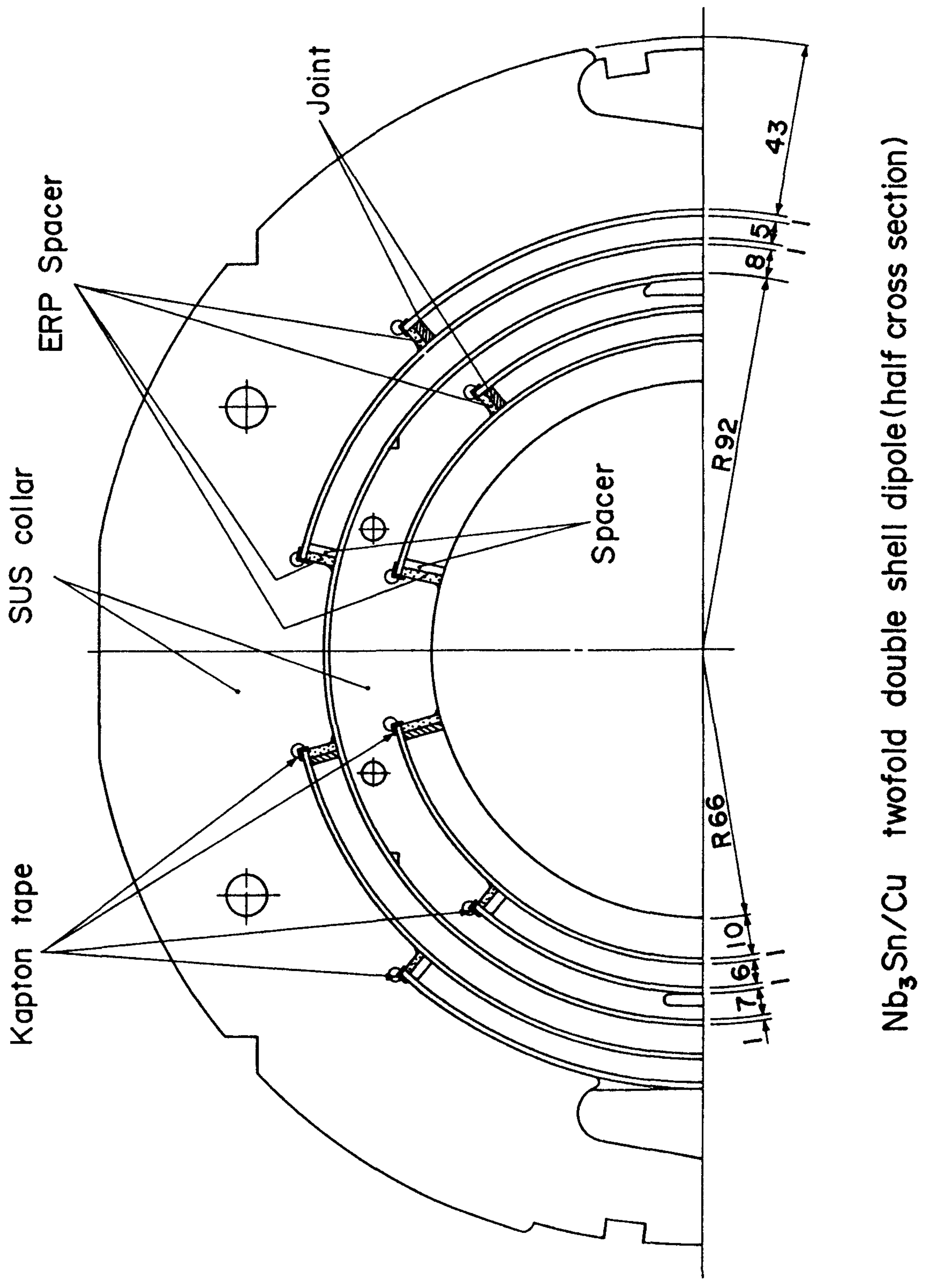

Figure 5. Schematic cross section of twofold duble shell Nb_3Sn/Cu dipole

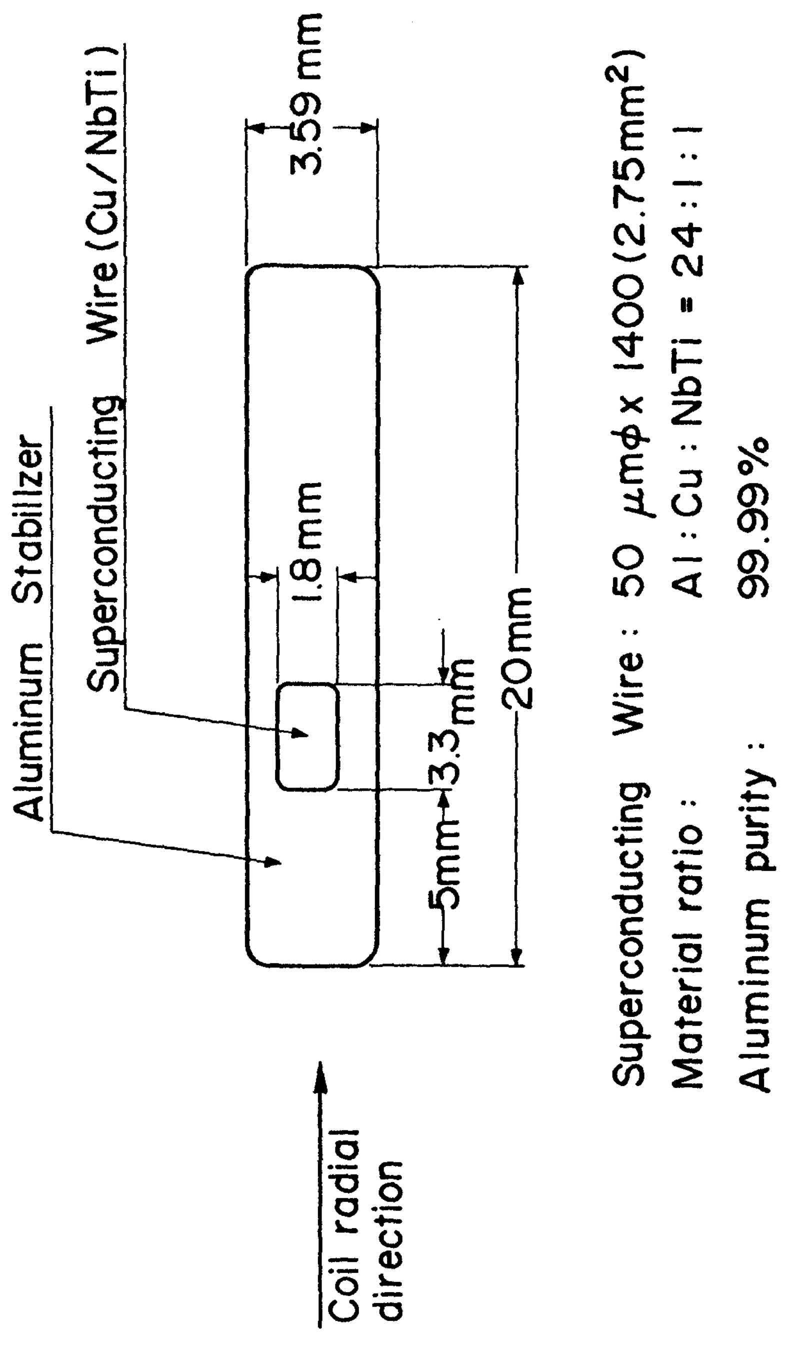

Figure 6. Cross section of aluminum-stabilized NbTi/Cu conductor