SURVEY OF EXPERIMENTAL FACILITIES IN EU LABORATORIES RELEVANT TO CONDUCTOR R&D FOR FUTURE ACCELERATOR MAGNETS

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Abstract
A critical evaluation for possible application in future accelerator magnets of existing and newly developed superconductors requires knowledge of their properties by experimental verification under representative operational conditions. A first attempt is made to define the experimental requirements to enable such an elaborate evaluation and to survey the availability and the capabilities of existing measuring facilities in Europe..

1. CANDIDATE CONDUCTORS FOR FUTURE ACCELERATOR MAGNETS

1.1 NbTi

With the development of the LHC at CERN the ultimate performance limits of NbTi conductors operating at 1.9 K with maximum fields of about 9 T have been fully exploited, both for the main regular lattice dipole and quadrupole magnets and for the magnets in the IR regions close to the experiments. Without considering an even larger circumference of the present tunnel only limited upgrades of existing LHC components can be expected employing NbTi conductors.

1.2 Coated YBaCuO.

Despite their challenging (Jc,B,T)-properties and the rapid improvement of performance and long length production of coated YBCO conductors [2] possible large scale applications competing NbTi or Nb3Sn should not be expected within the coming 10-15 years. Besides, a comprehensive and generously supported research program hardly exists in Europe.

1.3 Nb3Al.

Despite its superior strain properties compared to Nb3Sn the difficulties in controlling and improving Jc(B.T), manufacturability, cryogenic stability, filament size and phase stability impedes (large scale) application of this very challenging superconductor in accelerator magnets within 15 years. In contrast to Japan and the United States no serious R&D programs on Nb3Al exist in Europe.

1.4 BiSrCaCuCo.

The research on BSCCO conductors during the last decade has been mainly focused on 50-60 Hz AC, low field power applications of BSCCO-2223 tape conductors. A well concerted effort on basic material research and demonstrator development for a wide range of possible applications has been significantly supported by both the European commission within the 3rd, 4th and 5th EU Framework Programs and by national research programs. Despite the establishment of a well organized, lively and highly competent R&D community the European Commission has not approved a single BSCCO proposal within the present 6th framework program.

Applicability of the present generation of BSSCO conductors in accelerator magnets is not attractive regarding the awkward tape geometry, the relative large filament size, the lower engineering current density Je if compared to Nb3Sn, the Jc-strain sensitivity and the conductor costs. Regarding the above discussed funding situation also application of BSCCO conductors in accelerator magnets cannot be expected within 10-15 years.

1.5 MgB2.

The critical properties of the most recently discovered superconductor MgB2 appear to be very challenging as a possible competitor of NbTi at relatively low fields at elevated temperatures (~20 K) and possibly also as a very high field LTS conductor. The present R&D is organized mainly in national programs in many European countries. Only 1 EU-fp6 program at present has been awarded: "HIPERMAG" is a 2.5 M€ funded, 3 years program involving 13 partners from 9 EU-countries and focuses mainly on optimization of material properties and control of the manufacturability of multi-filamentary conductors. Considering more specifically application in high Jc high field accelerator magnets, at present no specific benefits in performance, mid-term availability and price compared to NbTi are expected.

1.6 Nb3Sn.

European R&D of Nb3Sn conductors has been driven mainly by the EFDA/ITER program for application in fusion reactors. A significant concerted effort by industry and research centers has resulted in a quality controlled, large scale production of large CICC's containing Nb3Sn wires exhibiting a moderate Jc (800-1200 A/mm2 @ 12 T) and low losses by controlling both the filament size (~5-10 µm) and the wire contact resistance. Investigations in this program on the Ic –strain sensitivity focus mainly on the longitudinal strain though also other strain components (bending strain, pressed wire to wire contacts) contribute significantly to the local strain state under Lorentz forces in CICC's.

It is remarkable that in contrast to laboratories in Japan and the United States, despite several interesting R&D programs in Europe confronted with performance limitations of Nb3Sn conductors, only the University of Geneva and the Bochvar Institute in Russia have reported on more fundamental aspects of these limitations. These aspects comprise for instance grain growth during the heat treatment, the specific influence of ternary or quarternary additions to the Nb3Sn, Sn gradients in the Nb3Sn layer and the corresponding critical properties of Sn deficient, of-stochiometric parts of such layers.

Despite the complexity of Nb3Sn coil manufacturing several well performing model dipole magnets have been realized since 1990 illustrating the potential of Nb3Sn conductors in this field. The enormous improvement in Jc, mainly the result of a well organized DOE funded program in the US, has further opened challenging prospects of application of Nb3Sn conductors for accelerator magnets and coil manufacturing technology.

To summarize above, only Nb3Sn conductors show the potential for application in a next generation of high-field, large bore, field quality accelerator magnets in a timeframe of 5-10 years. Therefore this survey on measuring facilities focuses mainly on issues related to Nb3Sn superconductors.

2. NB3SN ACCELERATOR MAGNET PROGRAMS IN EUROPE

After the successful performance of the 11 T dipole magnet MSUT in 1995, developed by the University of Twente, it lasted till 1998 till two mainly technology oriented, moderately funded European programs were established aiming at the realization of model accelerator type Nb3Sn magnets. A CERN-University of Twente program focuses on an 88 mm bore, 10 T, high field quality model dipole magnet. CEA/Saclay develops a model of a Nb3Sn version of the existing LHC lattice quadrupole magnet, which will be possibly used as a final focusing magnet inside the TESLA detector.

In January 2004 the EU-fp6 research program NED, part of the Integrated Activity Care, has started its activities towards a 90 mm bore, 15 T model dipole magnet which can be used as an upgrade of the 10 T limited conductor test facility FRESCA at CERN. Due to limited funding in Phase 1, this program focuses mainly on Nb3Sn conductor development at European industry aiming at a conductors exhibiting a non-copper Jc of 1500 A/mm2 @15 T, 4.3 K, a Cu:Sc ratio of 1-1.2 and a filament size smaller then 50 µm. The conductors should be capable to withstand transverse pressures of up to 160-180 MPa. In phase II, which has not yet been approved for funding, the manufacturing of the magnet system should be realized.

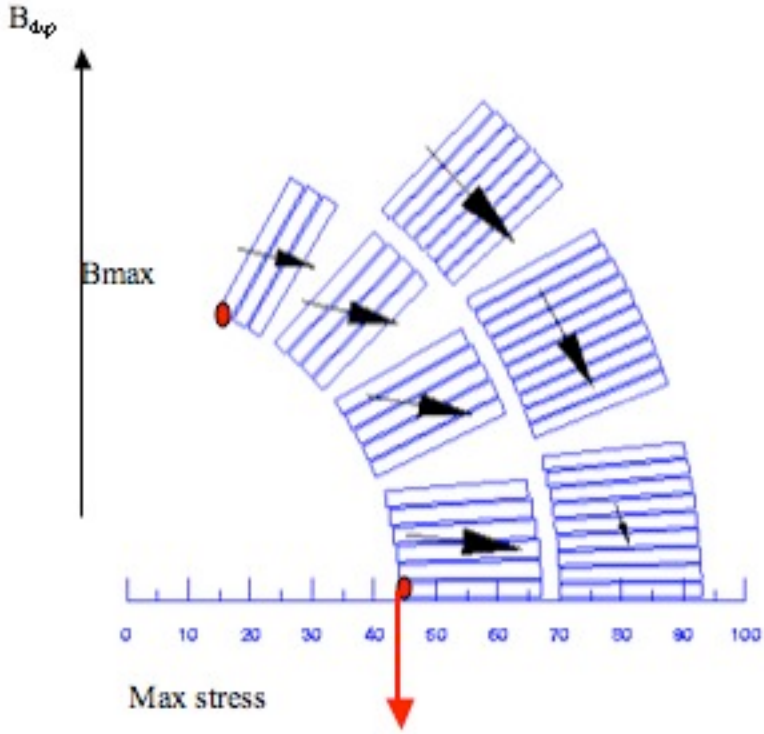

Figure 1. Possible conductor arrangement for the 90 mm bore, 15 T NED dipole**.**

Though the NED program includes a limited effort on magnet design Figure 1 shows a proposed cross section of the coils. The Rutherford cables in this design contain 30-32 strands of 1.25 mm diameter and a stainless steel core to limit the Rc to about 40 100 µΩ. For the moment only the wind-and-react method for coil manufacturing is considered.

3. FACILITIES TO MEASURE CRITICAL CONDUCTOR PROPERTIES

3.1 Wire requirements

To obtain magnets with required field amplitude and field quality, operating reliably for many years, conductor properties and coil manufacturing should reach a high level of control, reproducibility and reliability. Especially quality control of the conductor properties and performance is a prerequisite for successful magnet operation.

The flow diagram in Figure 2 shows qualitatively the relation between the properties of the wires developed and delivered by the manufacturers on magnet performance. The red/bold marked properties require critical experimental verification.

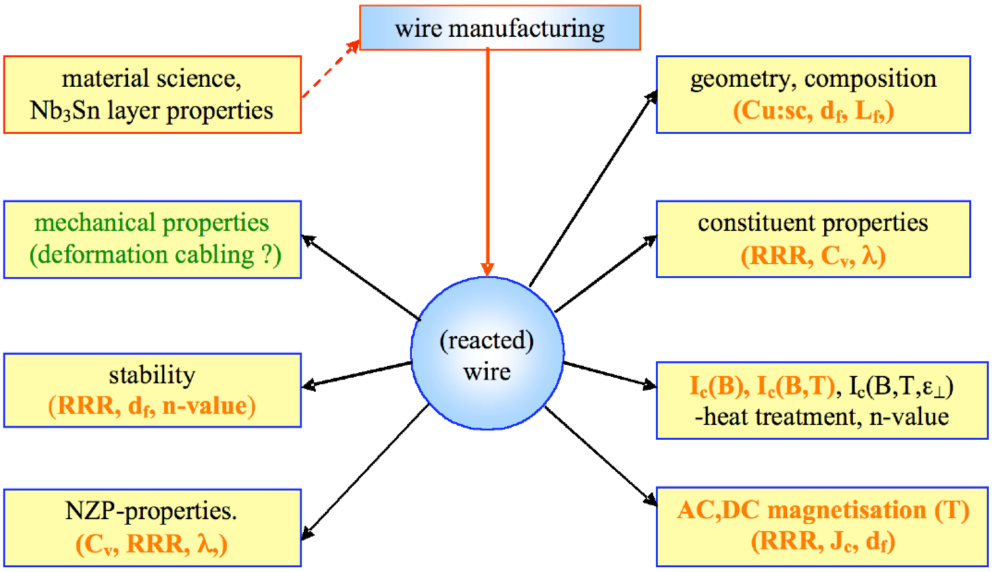

Fig. 2. Schematic presentation of the relation between the conductor properties which should be known by measurement (in red/bold) and their impact on magnet performance.

3.1.1 Measuring facilities for $C_v(T)$ and $\lambda(T)$.

The determination of the matrix RRR, the Cu:Sc ratio, the filament pitch L_p and the geometrical filament size d_f is rather straightforward and is routinely carried out at both by manufacturers and by users.

Facilities to measure $C_v(T)$ and $\lambda(T)$ at cryogenic temperatures of the wire constituents or of the composite itself are summarized in Table I.

Table I. $C_v(T)$ and $\lambda(T)$ Measuring facilities in Europe

	$C_v(T)$	$\lambda(T)$	remarks
University of Geneva (home built facility)	X		small samples
University of Southampton (PPMS)	X		
Johannes Keppler Institue (PMMS)	X		
CEA Saclay		X	insulated cable stack (1.8K)
University of Twente		X	idem (4.3 K)
INFN-LASA		X	idem (4.3 K)

Though many but mostly contradictory data from different sources are widely available it is highly recommended to establish a world-wide data base on material propeties which contains indisputable data of relevant material properties at cryogenic temperatures.

3.1.2 $I_c(B)$ or $I_c(B,T)$ measuring facilities on wires

Especially the sample preparation and the measurement of $I_c(B)$ or preferably $I_c(B,T)$ of very high current density Nb_3Sn wires is rather demanding. Because of the strain sensitivity of I_c the mounting history and the materials choice is determinative for the measured I_c at a certain field. However, so far no alternative procedures other than the standard ITER procedures exist for sample handling during the heat treatment at about 650 ^{0}C and the mounting of the reacted wire on the sample holder for critical current measurements of very high current density wires. As an example, Figure 3 shows the expected critical current at 4.2 K of the proposed Nb_3Sn wires for NED.

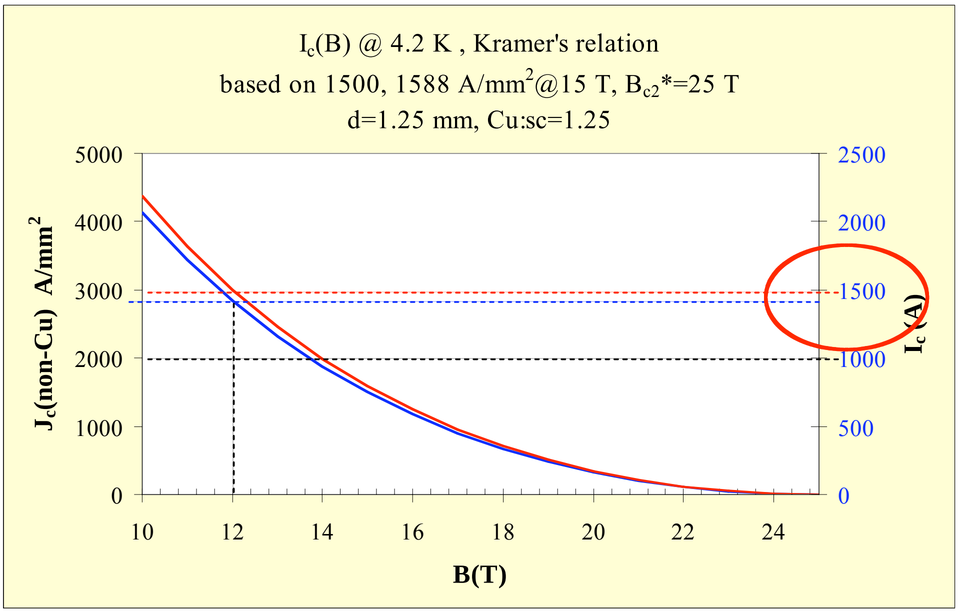

Fig. 3 Expected $I_c(B)$ at 4.2 K of a 1.25 mm Nb_3Sn wire in the NED program with a non-Cu J_c of respectively 1500 and 1588 A/mm^2 @ 15 T.

Compared to e.g. ITER Nb_3Sn wires with a typical I_c of 500 A @ 12 T the rather high critical currents at relatively high fields of the next generation of Nb_3Sn conductors put severe demands on the existing measuring capabilities in Europe. Only a few institutes in Europe have reported experience on such high current/high field measurements at low electric field levels (< 1 μV/m), but the results may still vary by about 10 %, which is rather poor if I_c serves as a quality parameter.

3.1.3 Wire magnetisation measuring facilities

Filament magnetization resulting from persistent currents have a direct impact on the field quality of accelerator magnets at low fields during particle injection in the accelerator. A more indirect effect occurs during particle injection when the current through the coils is kept constant but the filament magnetization and therefore all field components nevertheless show a time-dependent decay. During the first few mT of the field ramp after particle injection the field components snap-back to the value at the beginning of the particle injection. Decay and snap-back result from a rather subtle interplay between the filament magnetization and the slow redistribution in the coils of so-called Boundary Induced Coupling Currents (BICCs).

Though the misleading concept of an effective filament diameter is widely used, it is the magnetization M ~(J_cxd_f) which is determinative for above static and time-dependent field errors. Since the present generation of of high-current density Nb_3Sn wires still exhibit a rather large magnetization below 2 T, knowledge of M is imperative and can only be obtained by direct magnetization measurements. Also for fast cycling magnets with a dB/dt in the range of several T/s experimental determination of M and matrix coupling current losses are strongly required.

Several laboratories in Europe are capable to measure the filament magnetization M by the Vibrating Sample Magnetisation technique, SQUID Magnetisation or the standard pick-up coil technique at relevant field strengths (up to 4T) and temperatures (1.8-4.3 K). Only the pick-up coil technique enables AC-loss measurements at field sweep rates of 0.1-1 T/s. Despite the resembling techniques differences in the range of 20 % between different laboratories are no exception.

3.2 Rutherford cable requirements

Since for accelerator magnets only the usage of high current Rutherford cables is considered figure 4 shows similar to figure 2 the relation between the cable properties and their impact on magnet performance. It should be noted that the cable insulation is included in these considerations.

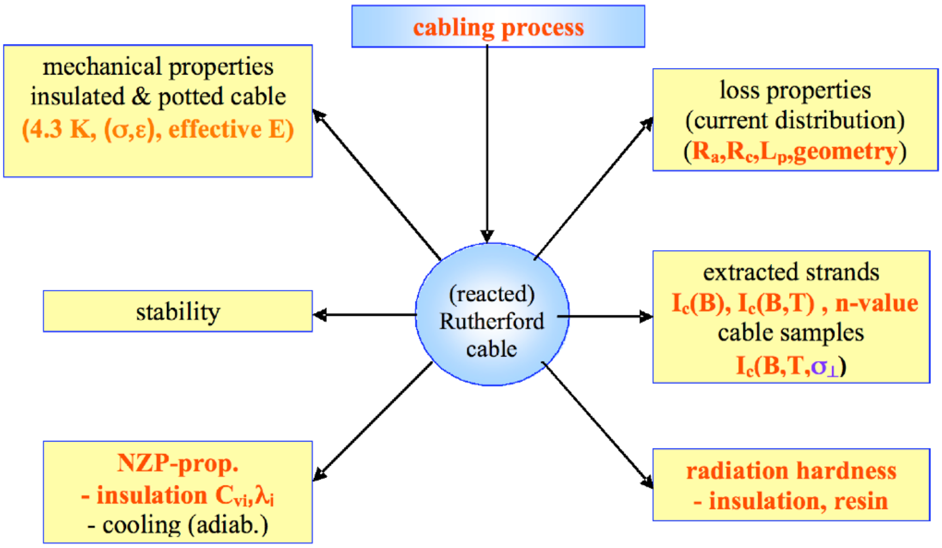

Fig. 4 Schematic presentation of the relation between the cable properties which should be known by measurement (in red/bold) and their impact on magnet performance.

3.2.1 Cabling facilities

Due to the large differences in hardness, Young's modulus and yielding properties of the materials inside non-reacted NbSn wires (Cu, Nb, eventually Ta barriers, Sn or highly densified powder) the cabling process into highly compacted Rutherford type of cables often results in damage of the internal wire structure. This is reflected by a current degradation compared to virgin strands larger than 10 % and tin contamination of the copper matrix during the heat treatment. This immediately implies that a good performing wire not necessarily results in a good performing cable. Since the relation between internal strand lay-out, the deformation history of the strands and the type of strand on one hand and the cable dimensions on the other hand are not well understood yet, the result of cabling of NbSn wires at present is rather a process of trial and error. It is characterized by an iterative learning process exploring the parameter space (cable width, thickness, pitch, keystone angle, core tension, wire tension) followed by microscopic inspection of the cross section or I_c measurements of heat treated extracted strands. To obtain a satisfying result (i.e. I_c degradation < 8-10 %, mechanical stability of the cable, good core position, acceptable residual twist) many of such iterations may be necessary. Even a complete adaptation of the strand lay-out may be required after this iterative process.

At present such an experimental cabling facility with skilled, experienced people does not exist in Europe.

3.2.2 $I_c(B)$, $I_c(B,\sigma_\perp)$, NZP, current distribution and stability measuring facilities for cables

The well known I_c dependency of Nb_3Sn conductors on axial strain manifest itself in a different way in Nb_3Sn accelerator magnets. In this case however the perpendicular stress component determines the occurrence of I_c reduction or permanent I_c degradation of the cables. Presently a stress limit of

150 MPa is used in high-field magnet design and the performance of all Nb_3Sn model magnets tested have shown that this is an appropriate limit. Typical I_c behaviour of different Nb_3Sn Rutherford cables under transverse pressure is shown in figure 4 resulting from experiments at the University of Twente.

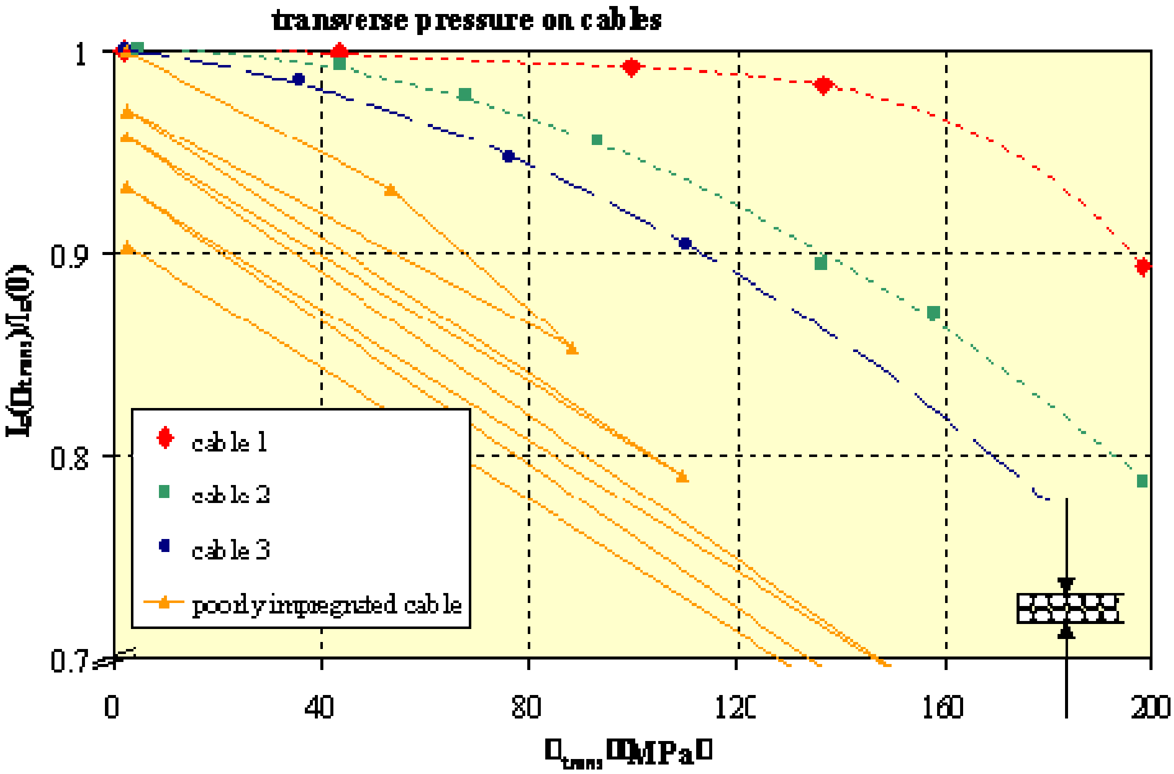

Fig. 5 Typical reduction of the normalized critical current of 3 different Nb_3Sn cables under transverse pressure @ 11 T, 4.2 K. At pressures above 160 MPa permanent I_c degradation occurs for most cables. Also shown is the behaviour of a cable which lacks of compete resin penetration inside the cable.

The I_c sensitivity to transverse pressure is not well understood yet in terms of cable and strand properties and should be measured for each specific strand-cable-insulation-core combination.

$I_c(B)$ measurements of cables are preferred above I_c measurements on extracted strands. The subsequent handling steps of strand extraction, heat treatment and final mounting on a sample holder demand utter caution and are rather prone to introduce additional damage to the filaments. Like for regular I_c measurements on virgin wires hardly any reported experience exists on such high current density wires extracted from Rutherford cables.

Also NZP, AC loss and stability measurements on cables are to be preferred above indirect measurements of related wire c.q. cable properties. In table II the capabilities of existing facilities for cable measurements are summarized.

Table II. Exisiting facilities for cable measurements

	CRPP SULTAN	Cern FRESCA	UT		FZK FPI
current supply	cold transformer	RT-PS or cold transformer	cold transformer		RT-PS
sample current (kA)	100	40	45		10
max. field (T)	11 solenoidal	10 dipole	15 soldenoidal		14 split pair
operating temperature (K)	> 4.3 forced flow He	1.8 or 4.3	4.3		4.3
max. field region/ sample length (m)	0.4	2 x 0.7	0.04 (U-shape)	0.6 (helical)	0.4
$\sigma_{\perp}$ (MPa)	RT prestress possible	RT prestress < 100	< 250	-	axial tensile stress only
NZP/stability meas.	yes	yes	no	no	possibly
experience/capability current distribution measurements	yes/yes	yes/yes	yes/no	yes/no	no/no
additional features	- AC field 0.4 T 0.01-6 Hz - 3 T pulse field	- Hall sensors curr. distr. meas.	-	-	-
sample preparation/ sample mounting	demanding/ demanding	demanding/ easy	demanding/ easy	demanding/ easy	demanding/ demanding

Both the SULTAN and FRESCA facility offer a wide range of relevant cable measurements. FRESCA is a very flexible, dedicated facility to investigate Rutherford cables whereas SULTAN is more suited for long lasting measurements on large CICC's. However, considering the expected I_c(B, 4.3K)-values for the proposed NED cables, shown in figure 5, only the SULTAN facility is presently suited to perform most of the required measurements on Rutherford cables. With the upgrade in 2004 of the magnet facility at the University of Twente dedicated (B, $\sigma_{\perp}$) measurements on short samples of 0.04 m have also become feasible.

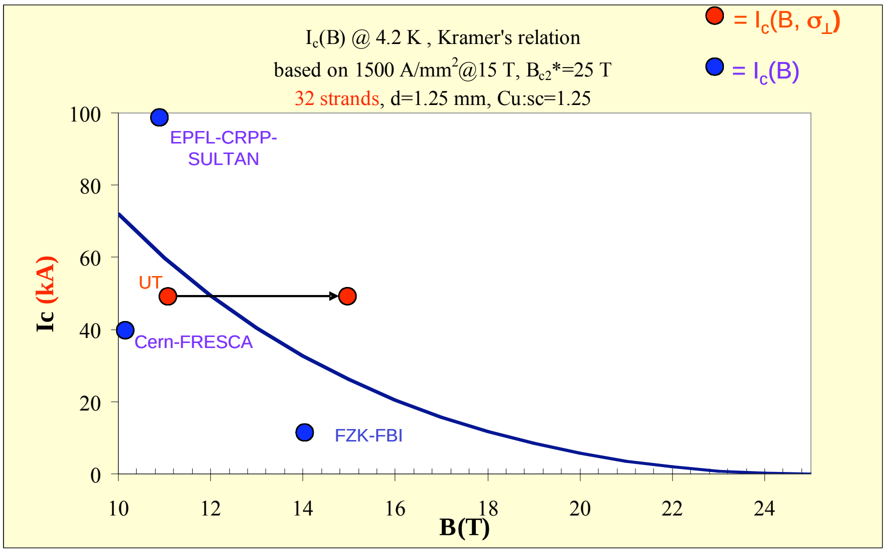

Fig. 6. Expected I_c(B) values for the proposed NED cable. Also shown are the measuring capabilities of existing facilities in Europe for cable measurements.

With the development of the 15 T NED dipole an upgrade of the very flexible FRESCA facility, dedicated for Rutherford cable research, becomes feasible and could offer unique services to the accelerator community.

Regarding its unique features for testing many relevant properties on a wide range of superconducting cables the SULTAN facility offers presently indispensable services to Europe.

3.2.3 Measuring facilities for Rc and Ra.

Though many parameters determine the amplitude and time constants of the different types of coupling currents, the dynamic field quality (including decay and snap-back) and the heat dissipation by the associated losses in accelerator magnets is mainly controlled by the resistance Rc between crossing strands in the Rutherford cables. For fast cycling magnets the preferred Rc value should lie in the 1-100 mΩ range, while for slowly ramped magnets Rc may range from 20 to about 200 μΩ. In both cases the resistance Ra between adjacent strands should be controlled accordingly.

Rc can be obtained by the V-I method proposed by Verweij, which principle is depicted in figure 7.

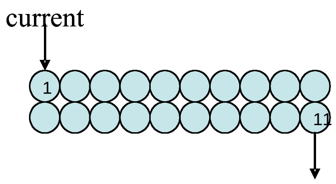

Fig. 7. Principle of the V-I method for R_c measurement.

Current is supplied to strand 1 and extracted at strand (Ns-1) on a cable piece of with a length of an integer cable twist pitches. By measuring the voltage between strand 1 and all other strands at the same longitudinal position at 4.2 K and under a representative transverse pressure, Rc can be derived. Though the method is rather inaccurate when Rc and Ra differ more than an order of magnitude this relatively simple method offers a good indication of the Rc range. Besides, it offers a convenient method to trace the evolution of Rc under cyclic loading of a cable stack, which is possible at the University of Twente, FZK and CEA-Saclay.

Rc can be obtained indirectly by measuring electrically or calorimetrically the losses of a cable stack of a few twist pitches long at 4.2 K under representative transverse pressure, exposed to an AC magnetic field oriented both parallel and perpendicular to the wide side of the cable. An additional feature of this method is that the total loss including strand coupling loss and hysteris loss is obtained. At present such measurements are carried out at the University of Twente and CCRP-Villigen.

4. SUMMARY.

For the last decade Nb3Sn conductor research in Europe has been mainly driven by the EDDA/ITER program accompanied by the development of dedicated measuring facilities for moderate-current density wires or large CICC's. Much experience has been gained to investigate experimentally the most relevant properties of Nb3Sn strands. The existing facilities are also adequate to investigate a new generation of high-current density Nb3Sn conductors.

However, for Ic(B) measurements or more dedicated NZP/stability measurements , both required on a routinely basis during the development of a new generation of very high current Nb3Sn Rutherford cables, the existing facilities are inadequate because of their lack of flexibility during sample interchange (costs, time) or because of their insufficient I(B) capabilities.

Regarding the complexity of cabling of high-current density Nb3Sn strands and the complete lack of experience in Europe on this issue it is highly recommended to set-up a European experimental cabling facility.