# PRESENT STATUS AND FUTURE PERSPECTIVES FOR NI-SHEATHED $MGB_2$ SUPERCONDUCTING TAPES

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**Abstract**
The present status of ex-situ Nickel-sheathed $MgB_2$ superconducting tape development is described. Typical critical current data of short conductors are presented as a function of the temperature and of the magnetic field. The results achieved so far on longer lengths are also reported and related to the short sample data. The lower critical currents observed in the longer tapes have been related to the damage of the superconducting core due to winding and to a residual fluctuation of the superconducting cross section observed along the tape length. Multifilamentary conductors, manufactured so far in short lengths, should represent the solution to solve the long length degradation.

## 1. INTRODUCTION

The recent discovery of superconductivity in $MgB_2$ at a temperature of 40 K [1] has immediately attracted the interest of the researchers searching for a new material to be implemented in various industrial applications. In spite of several years of continuous development, indeed, YBCO and Bi-2223 conductors still require substantial improvements, and it is not clear yet which material will reach a more desirable performance-to-cost ratio that will finally enable large scale applications in a liquid nitrogen environment. On the other hand, the recent progresses in cryogen-free cooling technology have opened new perspectives for the efficient use of superconductors cooled in the 20-30 K temperature range. High temperature cuprate superconductors have already gained a clear benefit from the possibility to lower their working temperature, and in very recent times several examples of fully functional devices have appeared, most of which based on Ag-sheathed Bi-2223 multifilamentary tapes. In the next future, these devices are expected to reach the market, especially that of AC applications, basically in the field of improving the power quality [2].

On the other hand, the potential current carrying capability of the $MgB_2$ phase has been also studied over the same temperature domain, soon after its discovery. First critical current measurements performed on polycrystalline samples by Bugoslavski et al. [3] have shown that grain boundaries are virtually transparent for the intergrain critical current flow. At 20K, irreversibility fields in the range 3-5 Tesla have been reported on polycrystalline samples, and relevant inductive critical currents for magnetic fields up to 1-2 Tesla have been measured [3]. These preliminary critical current values are roughly comparable to those of the present state Ag-sheathed Bi-2223 and Bi-2212 superconducting tapes for similar temperature-field conditions. Following this observation, the search for a suitable procedure for the fabrication of polycrystalline $MgB_2$ wires has been immediately started.

The idea of implementing the well-known Powder-In-Tube method to the fabrication of $MgB_2$ conductors has been successfully accomplished short time after the first experiments [4-6]. While different solutions to manufacture $MgB_2$ wires and tapes have been also studied [7], indeed, the Powder-In-Tube method has been widely preferred thanks to the peculiar properties of the compound. The rather small $MgB_2$ grain size, the relatively long coherence length, and the almost complete absence of granular behaviour are all positive aspects in favor of the use of the PIT method.

Relatively high critical current values were first reported on monofilamentary tapes, prepared by filling reacted $MgB_2$ powders inside metallic tubes, and by carrying out the typical mechanical deformation by wire swaging, drawing and rolling to thin wires or tapes without applying any heat treatment to sinter the grains [8,9]. These conductors however presented fairly reduced $T_c$ values (about 30 K ) compared to the expected one ( about 38 K ), due to a poor grain connectivity and a high lattice strain induced by cold working, and accordingly their high temperature behaviour has been negatively affected.

Following these early understandings, both in-situ and ex-situ processing routes for the manufacturing of $MgB_2$ conductors have been proposed: in both cases the conductor undergoes a final heat treatment at high temperature after the mechanical deformation, that can be either a simple sintering or a complete phase formation process. These approaches have definitely narrowed the many options for the choice of the sheath material that are theoretically possible, because a chemical compatibility with the $MgB_2$ compound is now required. Results have been reported with most of the workable pure elements and alloys, but the most promising results have been reported so far with Iron, Nickel, and Copper sheaths. Best transport properties at temperatures around 20 K are achieved on conductors that undergo a heat treatment at temperatures of the order of 900°C, and only Iron or Nickel can sustain such a high temperature without completely poisoning the $MgB_2$ phase.

Our choice has been particularly focused on $MgB_2$ conductors manufactured with high purity Nickel sheath, mainly because of electrical stability reasons. Furthermore, Nickel can be easily turn into a non magnetic material by appropriate alloying with Chromium or Vanadium. The ex-situ route has been preferred for the scaling up of the manufacturing process, because it is believed, on a first stage, to be probably more reproducible over long length than the in-situ process. It is indeed very difficult to achieve a correct mixture of very fine Mg and B grains to be homogeneously reacted inside the sheath, especially for multifilamentary conductors where filaments can be very thin.

## 2. EXPERIMENTAL

Monofilamentary and multifilamentary Nickel-sheathed $MgB_2$ tapes have been prepared by means of the PIT method following the ex-situ route, that differentiates from the in-situ one by the filling of already reacted $MgB_2$ powders into the metallic tube of typical size 12.7 mm x 6.0 mm ( outer diameter x inner diameter ) and up to 2 meters in length.

$MgB_2$ powders were either commercial ones, manufactured by HCStarck, or as a result of the reaction from amorphous Boron and Magnesium mixtures. In both cases, similar results in terms of final tape properties have been achieved. After packing the reacted powders inside the Nickel tube with an initial density of about 1.5 g/cm$^3$, they are cold worked by swaging, groove rolling and finally by drawing in many steps without intermediate annealing to round wires of about 1.5-2.0 mm in diameter. Then the wires are cold rolled to flat tapes of about 4 mm in width and 0.35 mm in thickness, with a superconducting filling factor of about 17%, i.e. an average transverse superconducting cross section of 0.24 mm$^2$.

Multifilamentary tapes are fabricated by a similar process, in which seven pieces of hexagonal monocore wires are stacked inside a second Nickel tube, that undergoes again the entire mechanical deformation process. In the unreacted state, $MgB_2$ tapes carry an appreciable critical current at 4.2K, of the order of $10^5$ A/cm$^2$, as a consequence of the high powder packing density that is achieved by the cold working procedure; on the other hand, the transport properties at higher temperatures or in an applied magnetic field are strongly limited by the reduced $T_c$ value ( about 30 K ), which is a consequence of the large $MgB_2$ lattice strain induced by the prolonged cold working procedure. A final heat treatment at about 900°C in Argon atmosphere is therefore required, mainly to recover the original $T_c$ value by partially healing the accumulated lattice strain, and to improve the grain connectivity.

The manufactured $MgB_2$ conductors have been characterized by means of transport critical current measurements at 4.2 K. Self field critical currents have been measured as a function of the temperature, while the magnetic field dependence of the critical current of short samples have been measured both at the INFN-Genoa laboratories in a field up to 2 Tesla, and at the Grenoble High Magnetic Field Laboratory (GHMFL), in applied fields up to 20 Tesla oriented both parallel and perpendicular to the superconducting tape surface. The pancake samples have been measured at the INFM-Genoa laboratory with an applied backup field up to 5 Tesla.

## 3. RESULTS

The self field as well as the magnetic field dependence of the critical current of short portions of monocore $MgB_2$ tapes cut from 200 meter long conductors are reported in fig. 1. The self field critical current values are very high and in excess of 100 A at all the temperatures we have measured. The magnetic field strongly depresses $I_c$ though, especially at high temperatures. Only at 20 K, a field of 2 Tesla does not reduce $I_c$ much below the desired 100 A level. Measurements have been performed for different orientations of the magnetic field with respect to the tape, but the anisotropy of the critical current is not significant at temperatures of 20 K and above, at least for fields up to 2 Tesla.

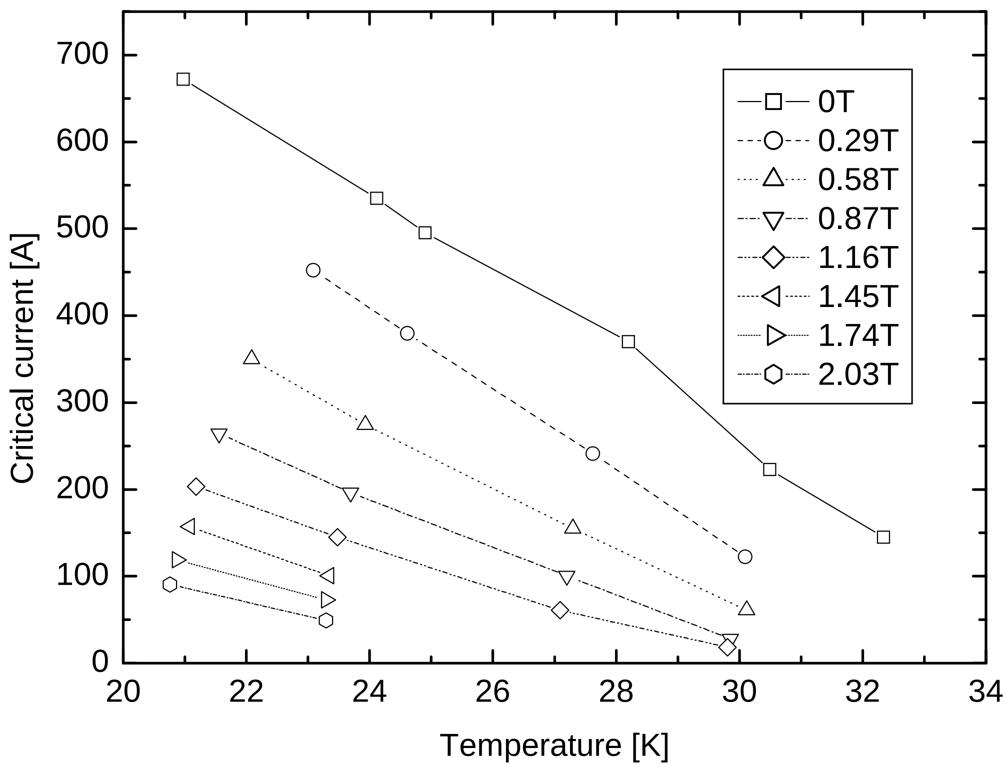


Fig. 1: Critical current as a function of the magnetic field and of the temperature between 20K and 33 K.

The situation is quite different at 4.2K, as shown in fig. 2, where the anisotropy of the critical current is reported for the same conductor, and is evident above 4 Tesla. In this case, the 100 A critical current level is reached for a magnetic field of 5 Tesla applied parallel to the tape widest surface. The critical current is not measurable for fields below 1 Tesla because it is well in excess of 1000 A. Self field critical current density at 4.2 K extrapolates to a value of about $10^6$ A/cm$^2$, while irreversibility fields are of the order of 8 T and 12 T with the field oriented perpendicular and parallel to the tape, respectively. These values are typical for polycrystalline $MgB_2$ materials and are in between the values commonly reported for single crystals, which are especially low [10], and for the thin films, which can be instead much higher, in some cases in excess of 50 Tesla [11].

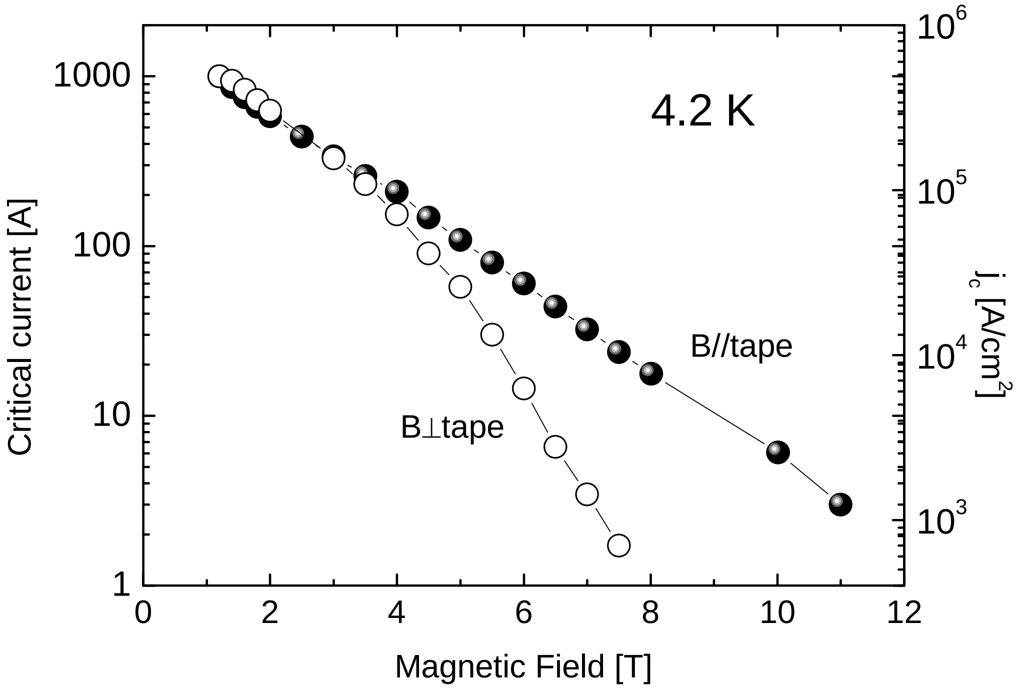


Fig. 2: Anisotropy of the critical current at 4.2 K measured for a monocore tape up to a field of 11 Tesla.

The manufactured conductors have been initially used to realize a series of pancakes, both with the react and wind (R&W) as well as with the wind and react (W&R) process. About 10 meters of monofilamentary tape have been used for each pancake. The critical current of the pancakes have been measured at 4.2 K in liquid helium bath. An additional magnetic field up to 5 Tesla has been superimposed to the field generated by the pancake. The critical currents of the R&W and W&R pancakes have been reported as a function of the magnetic field in fig. 3, together with the short sample critical current reported in fig. 2. The W&R pancake presents a critical current value that is much nearer to the short sample critical current than the R&W pancake. The latter presents a critical current that is only about 60% the short sample critical current.

The drop in critical current between the W&R and the R&W pancakes can be directly attributed to the mechanical damage induced on the tape by the handling and winding procedure. As the inner diameter of the pancakes is 50 mm., and the superconducting core of the tape has an average thickness of about 80 μm, it results that the bending strain applied with the winding reaches about 0.16%, i.e. of the same order of magnitude of the critical strain value of our monocore $MgB_2$ tapes.

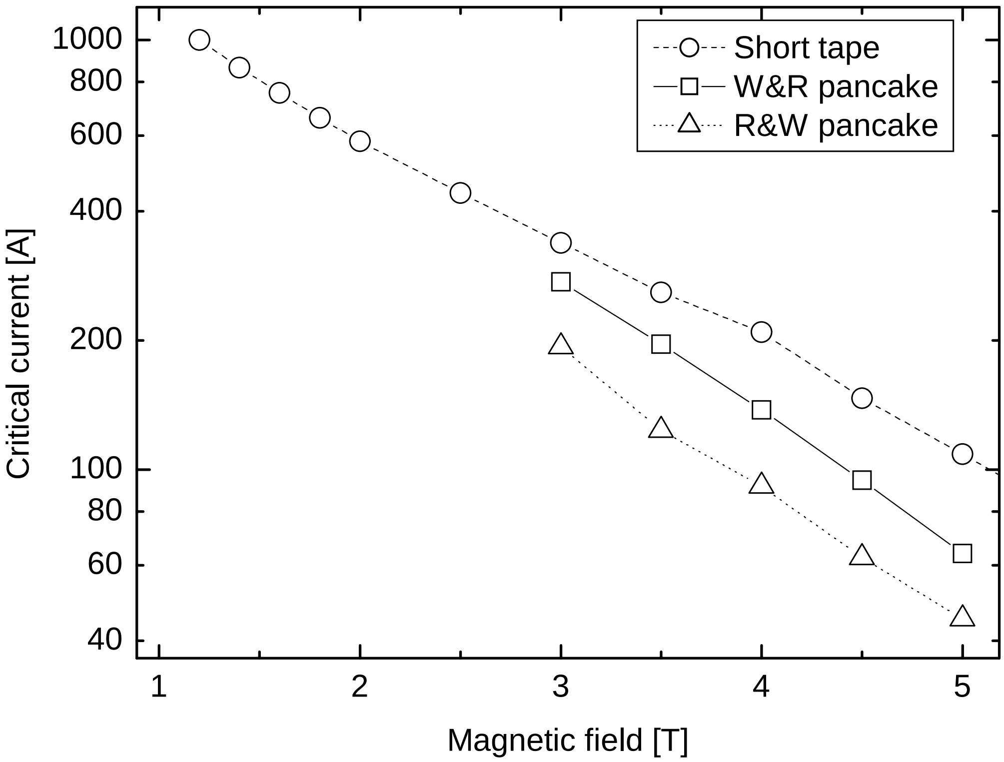


Fig. 3: Critical currents at 4.2 K as a function of field for a W&R pancake, a R&W pancake, and a short tape for comparison.

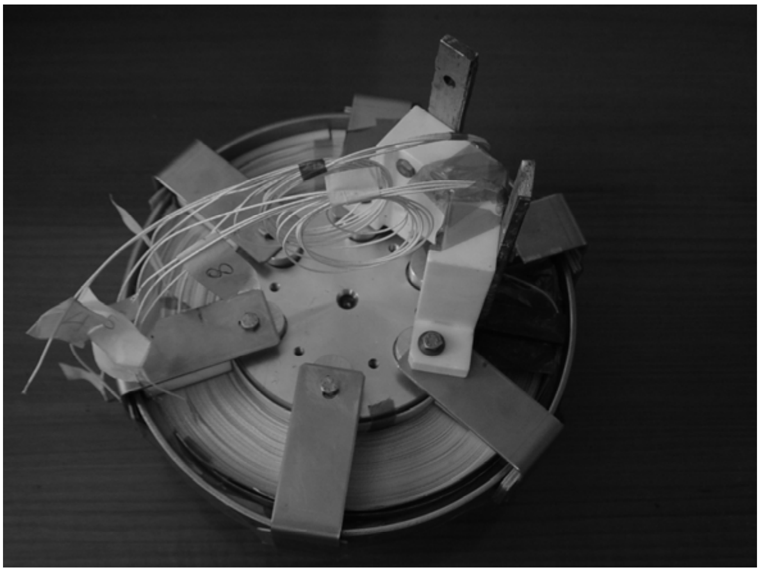

Fig. 4: Picture of an $MgB_2$ pancake realized with 100 meters of monocore tape.

To reduce the effect of the bending strain and to study longer portions of conductor, R&W pancakes have been realized with larger inner diameter of 120 mm and with up to 100 meters of tape. A picture of one of these pancakes manufacture by Ansaldo Superconduttori SpA is presented in fig. 4. Ansaldo Superconduttori has built setups for the large pancake measurement both in liquid helium, as well as in a cryogen free environment. Preliminary critical current measurements of these pancakes have been performed at 4.2K in self field. The best pancakes typically quenched at a critical current of about 350 A, that corresponds to a maximum magnetic field on the conductor of about 0.8 Tesla. Again, a reduced critical current level is observed with respect to the short sample results.

A possible explanation for the reduced critical currents observed over the long lengths has been attributed to fluctuations of the transverse superconducting cross section. To investigate this hypothesis, sections of the pancakes have been cut and analyzed with the optical microscope in order to determine the superconducting cross sections at different positions along the conductor. An entire section of a pancake is shown in fig. 5 as an example. Preliminary analysis has revealed that the cross section of the superconducting core fluctuates by a factor of the order of ±30%. It is therefore possible that most of the critical current reduction over long lengths is caused by this effect.

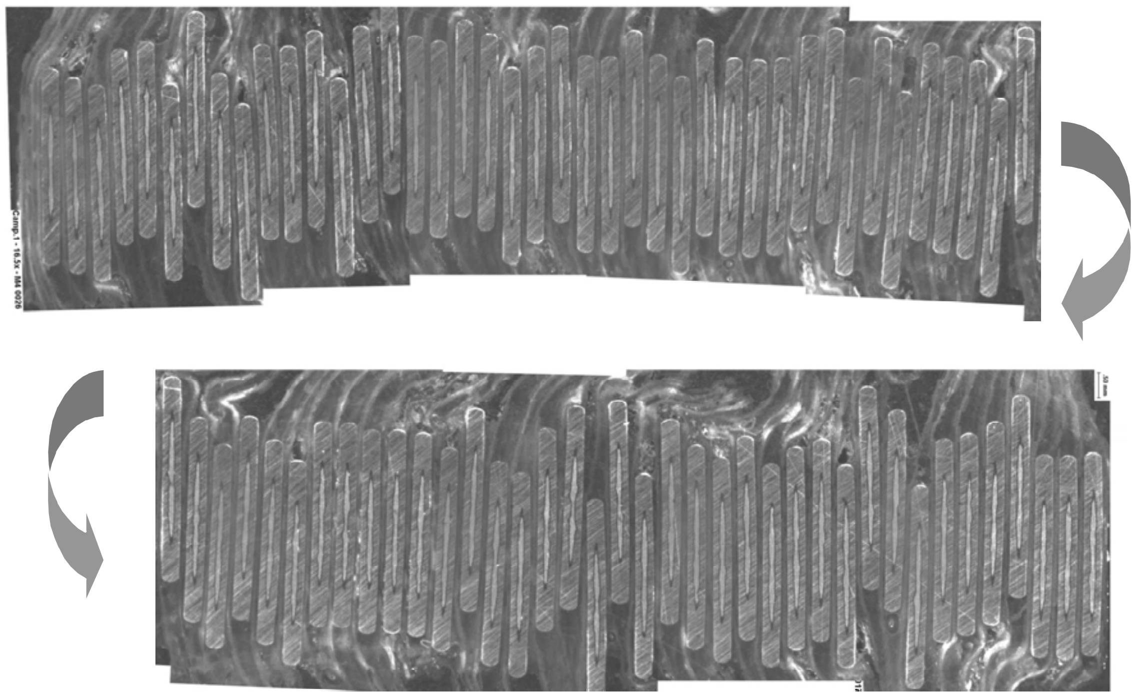

Fig. 5: Cross sectional cut of a pancake realized to study the local fluctuations of the monocore tape transverse cross section along the length.

In order to reduce fluctuation of the superconducting cross section along the tape length, and to improve the tape mechanical properties, multifilamentary conductors are required. Multifilamentary tapes have been therefore prepared as described in the previous paragraph. As Nickel reacts with $MgB_2$, a very thin Niobium barrier has been introduced between the superconducting core and the matrix material to avoid a strong poisoning of the superconducting core. A typical transverse cross section of a 7-filament tape is reported in fig. 6. The best short samples realized with such a process have reached self field critical current densities very near to that of the monocore tapes, i.e. $10^5$ A/cm$^2$ and $10^6$ A/cm$^2$ at 30K and 4.2K, respectively. Preliminary testing of the mechanical properties of the multifilamentary tapes have shown that the critical bending strain can be increased to 0.3% without any change in the sheath material. Once developed in long lengths, the multifilamentary conductors will be therefore able to better withstand the conductor handling and winding during the pancake manufacturing by the R&W technique.

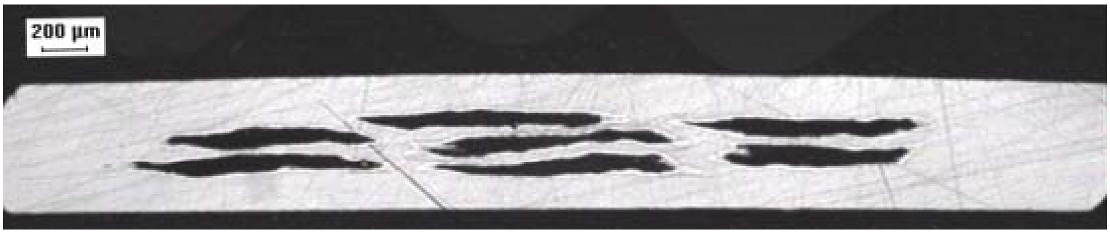


Fig. 6: Transverse cross section of a multifilamentary tape with similar critical current than the monocore ones. A diffusion barrier in Niobium is present around each filament.

## 4. CONCLUSIONS

In this paper the present state of Nickel sheathed $MgB_2$ superconducting tapes has been presented. Monofilamentary tapes have been already manufactured in pieces up to 100 meters in length, and used to wind pancakes. High critical currents have been measured at temperatures up to 20 K in moderate applied magnetic fields. The characterization of the short and long lengths has shown that monocore tapes are not the ideal configuration to be employed for the realization of windings. Fluctuations of the superconducting filament cross section, and its brittleness make R&W pancakes hardly feasible with a similar critical current level of the short lengths. Recent advances in the cold working procedure has allowed to realize multifilamentary tapes that show similar critical currents than the monocore ones, but capable of sustaining a larger bending strain and hopefully with a lower fluctuation of the superconducting cross section. If the development of these multifilamentary conductors will be successfully extended to lengths exceeding 1000 meters, it is expected that this conductor will become very attractive both for DC and AC applications operated in the temperature range between 20 and 30 K.

## 5. ACKNOWLEDGEMENT

The authors acknowledge the financial support of the European Network Human Potential Programme contract n. HPRI-1999-CT-00030 for the experiments performed at GHMFL.

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