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2013 Supercond. Sci. Technol. 26 115004

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# Local transport in multi-filamentary superconductors: longitudinal versus transverse dissipation

A Borroto<sup>1</sup>, L Del Rio<sup>1</sup>, E Altshuler<sup>1</sup>, M Arronte<sup>2,3</sup>, P Mikheenko<sup>4</sup>,  
A Qviller<sup>4</sup> and T H Johansen<sup>4,5</sup>

<sup>1</sup> Superconductivity Laboratory, IMRE-Physics Faculty, University of Havana, 10400 Havana, Cuba

<sup>2</sup> BRALAX, S. de RL., Tampico, TAMPAS, Mexico

<sup>3</sup> Technological Laser Laboratory, IMRE, University of Havana, 10400 Havana, Cuba

<sup>4</sup> Department of Physics, University of Oslo, NO-0316 Oslo, Norway

<sup>5</sup> Institute for Superconducting and Electronic Materials, University of Wollongong, Australia

E-mail: [ealtshuler@fisica.uh.cu](mailto:ealtshuler@fisica.uh.cu)

Received 27 June 2013, in final form 13 August 2013

Published 30 September 2013

Online at [stacks.iop.org/SUST/26/115004](http://stacks.iop.org/SUST/26/115004)

## Abstract

Little is known on the electrical properties of superconducting tapes and coatings in the direction transverse to the long dimension of the composite. However, transverse dissipation can eventually determine the fate of a transmission line in the case of failure due to the presence of transversal cracks, and is also crucial in the AC regime. In this paper we present a detailed experimental study of the electrical transport properties along the transverse direction of  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+x}\text{-Ag}$  tapes, and compare them with those measured along the long axis of the material. We study in detail the influence of the tape's microstructure on electrical properties along both directions by using sliding electrodes. Our measurements suggest that there is always dissipation in the transverse direction for any value of the current. We also demonstrate that the local dissipation in the transverse direction has a nontrivial correlation with the local density of superconducting filaments.

(Some figures may appear in colour only in the online journal)

## 1. Introduction

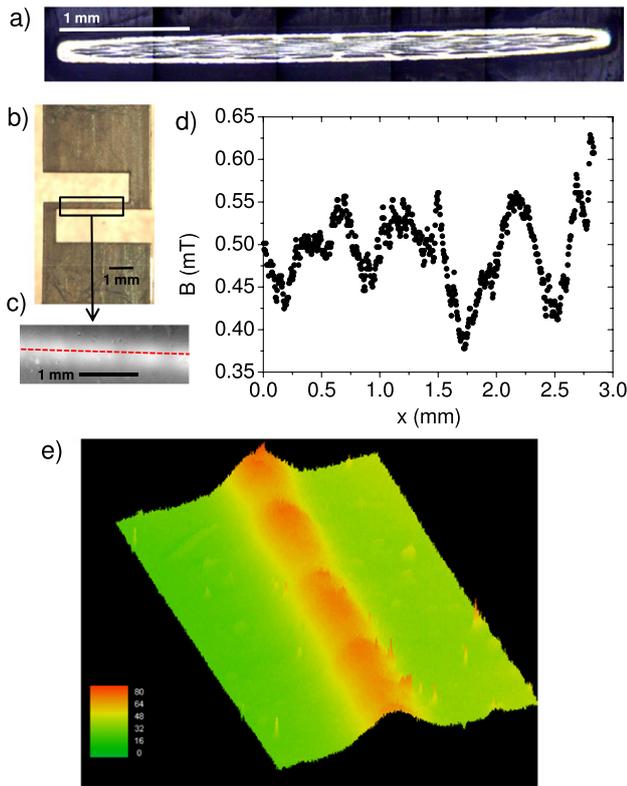
Inhomogeneities, being accidental or intended ingredients in a superconducting material have been, and still are, a major concern in developing viable applications. From bulk materials [1–5] to tapes [6, 7], coated conductors [8, 9] and thin films [10–12], the effects of inhomogeneities on the superconducting properties have been studied extensively—typically exploring the relations between structural morphology and the thermal, electric and magnetic properties.

In the case of tapes and coated conductors, the presence of extended defects, e.g. micro-cracks caused by bending strain, which inhibit the transport of supercurrent in the longitudinal direction, has been well documented [13–16]. In multifilamentary tapes, it is found that such defects do not affect significantly the inter-filamentary currents, which provide an 'escape' route in case of interruption of the

longitudinal current. Inter-filament currents are also of great relevance for losses in the AC regime [17, 18]. However, the transverse transport has been rarely studied in composite superconductors: most attention has been focused on the transport in the main direction.

In one such investigation, the transverse critical current in samples of an Ag-sheathed 55-filament  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+x}$  (Bi-2223/Ag) tape was studied using magneto-optical imaging (MOI) [19]. The results revealed that at 77 K the inter-filament current can be of the same order of magnitude at the currents flowing along the tape. When cooling the tape to lower temperatures it was found that the inter-filament coupling is much reduced—a scenario consistent with other MOI studies [20, 21].

Based on this, and following strong renewal of interest on Bi-2223/Ag tapes due to expected intensive use of liquid hydrogen [22], in which they still outperform other



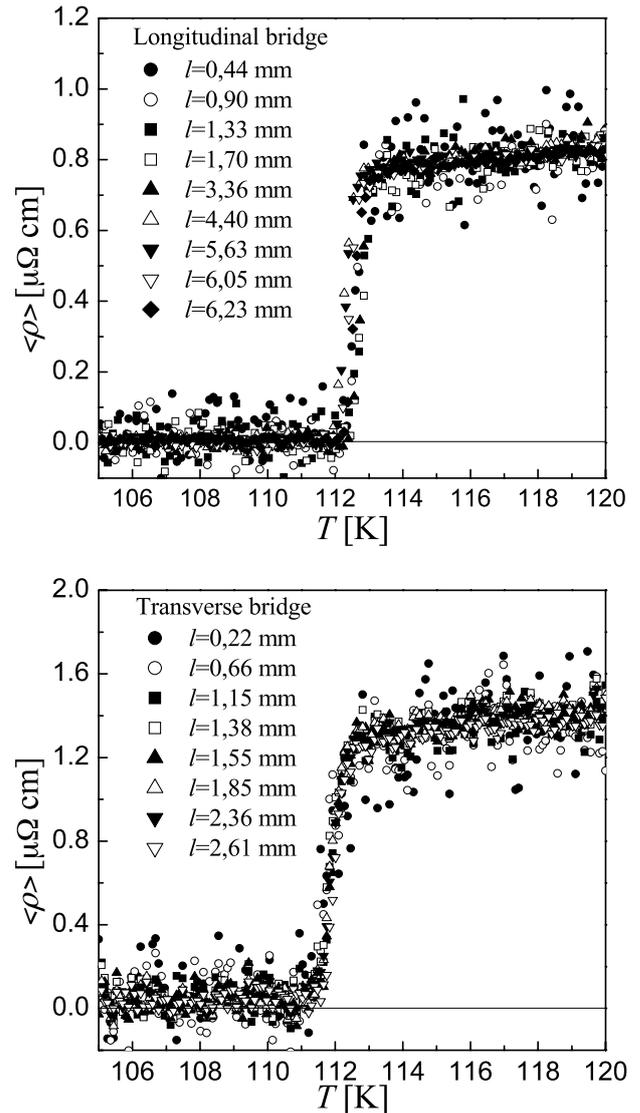
**Figure 1.** (a) Cross-section of the Bi-2223/Ag tape before laser cutting. (b) Photo of a transverse bridge of width 0.30 mm. (c) Magneto-optical image of the remanent flux density in a section of the bridge at 27 K, after having applied a maximum field of 85 mT. (d) Magnetic field intensity profile along the dotted line shown in (c). (e) 3D intensity plot corresponding to the magneto-optical image shown in (c) (brightness code in arbitrary units).

superconductors, it is of interest to perform direct transport measurements in the transverse and longitudinal directions simultaneously in the same tape. Sánchez *et al* have made such measurements by cutting transverse bridges out of Bi-2223/Ag tapes using a laser technique [23]. In the present work, we use the same approach to produce long transverse bridges, and then perform space-resolved voltage measurements along the bridge by means of a sliding electrodes system.

While in the longitudinal direction we always find temperature and current regions of zero dissipation, the transverse direction is always dissipative. Furthermore, we are able to correlate the transverse electric field profile with the local superconductor/metal ratio, which shows temperature dependent, nontrivial relations that may be used as a guideline for improvement of the morphology of multi-filamentary tapes.

## 2. Experimental details

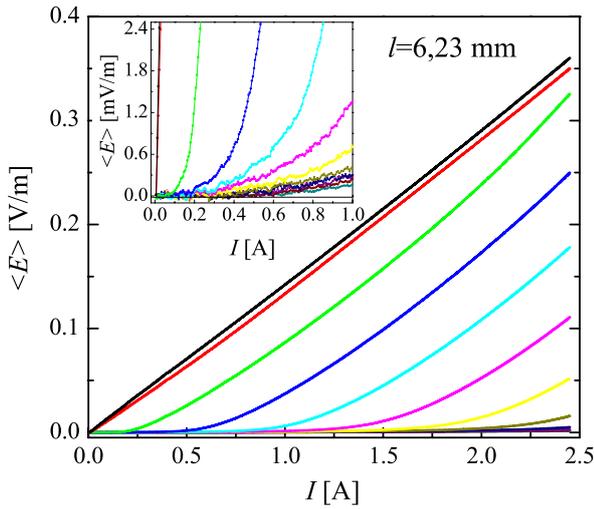
Samples were thin bridges cut from a Bi-2223/Ag tape in transversal and longitudinal directions. The original tape was 4.32 mm wide and 0.23 mm thick, and contained 61 filaments, as seen from its cross-section displayed in figure 1(a). Each filament is 0.3–0.4 mm wide and a few microns thick. The



**Figure 2.** Resistive transition of longitudinal and transverse bridges measured with various distances between the voltage contacts. One contact was fixed at the end of the bridge, while the second was stepwise displaced until reaching the other end.

engineering critical current of the tape was 65 A at 77 K, equivalent to a critical current density of approximately  $6540 \text{ A cm}^{-2}$ .

From a central area of the tape, transverse bridges were cut perpendicular to the longitudinal tape direction. A  $300 \mu\text{m}$  thick bridge is shown in the photo of figure 1(b). Panel (c) shows a magneto-optical image of the trapped flux distribution along the bridge at 27 K, taken with a  $4 \mu\text{m}$  thick ferrite garnet film as magneto-optical sensor [24] placed between crossed polarizers, so the image brightness represents the flux density [25]. The remanent state was achieved by first applying a magnetic field of 85 mT perpendicular to the tape plane. The clear contrast demonstrated in panels (c)–(e) implies that the filaments are superconducting and strongly trap magnetic flux. The modulation in the image brightness along the bridge results from the discrete filamentary structure of the sample. Using the Biot–Savart law as proposed in [19],



**Figure 3.**  $\langle E \rangle$ - $I$  curves for a longitudinal bridge. The curves, from bottom to top, were obtained at temperatures from 85 to 115 K, in steps of 2.5 K. Inset: zoom-in at the small current behavior.

we estimated an intra-filament critical current density of  $3.5 \times 10^4$  A cm $^{-2}$  at 27 K, which is a reasonable value, considering the engineering critical current of the tape at 77 K. From this characterization we conclude that the cutting technique has left the tape intact as far as the main superconducting features are concerned. Longitudinal bridges were prepared using the same method.

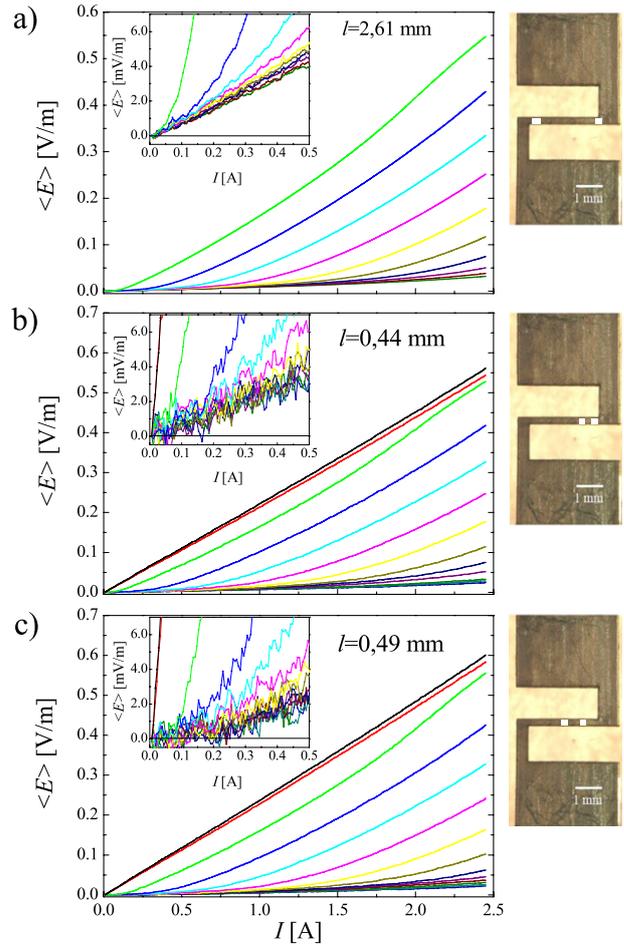
Transport measurements were performed using the four-probe technique, in which a voltage probe slid along the length of the bridge with a resolution of 0.2 mm. Resistance was measured using a Scitec Instruments 500 MC lock-in amplifier at 100 Hz, with a bias current of 1 mA through the sample, provided by a GW audio generator with a 1 k $\Omega$  resistor in series.  $I$ - $V$  curves were obtained at increasing DC currents provided by a Philips PE 1540 DC power supply, while the voltage was measured by a Keithley 2001 micro-voltmeter, with a resolution of 100 nV.

### 3. Results and discussion

#### 3.1. $\langle \rho \rangle$ - $T$ curves

Shown in figure 2 is the temperature dependence of the resistivity,  $\langle \rho \rangle$ , for a typical longitudinal (upper panel) and transverse bridges (lower panel). The resistivity was obtained from the measured resistance,  $R$ , using the formula  $\langle \rho \rangle = RS/l$ , where  $S$  is the cross-section area of the bridge and  $l$  is the distance between the contacts. All the curves for each bridge are basically similar, regardless the distance between voltage contacts. In particular, the longitudinal and transverse bridge have essentially the same  $T_c$  close to 112 K, and in both the width of the transition is  $\Delta T = 1$  K, which confirms a good quality of the superconducting material after laser cutting.

The resistivity in the normal state is  $\langle \rho_{\parallel} \rangle = 0.8 \mu\Omega$  cm and  $\langle \rho_{\perp} \rangle = 1.3 \mu\Omega$  cm for the longitudinal and transverse bridge, respectively. The average between those values is near the resistivity reported for silver alone at 120 K [26],

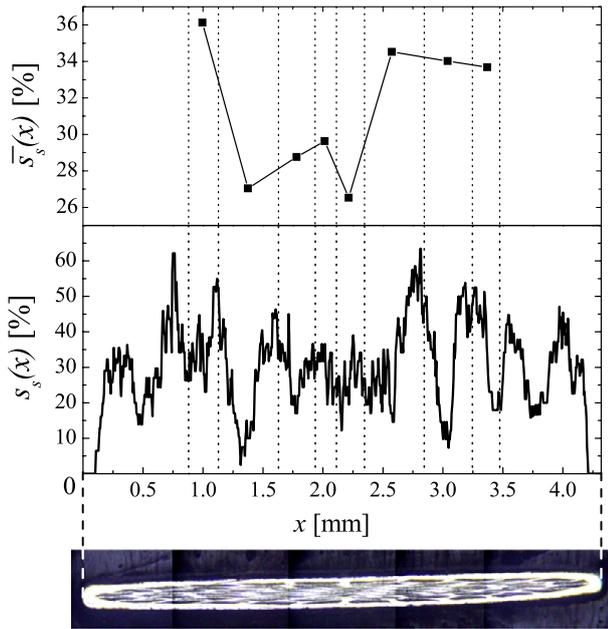


**Figure 4.**  $\langle E \rangle$ - $I$  curves for a transverse bridge. From bottom to top, the curves were obtained at temperatures from 85 to 115 K, in steps of 2.5 K. The panels (a)-(c) present data obtained with contacts located at different positions along the bridge, as shown in the images next to each panel.

which strongly suggests that the current mainly circulates through the inter-filament space in the normal state. This is also consistent with the fact that the normal state resistivity of Bi-2223 (reported as 150–800  $\mu\Omega$  cm in [27]) is much bigger than that of the silver, so currents ‘avoid’ circulating through the filaments. The difference between the normal state resistivity for the longitudinal and transverse bridges is expected from the fact that, in the longitudinal bridge, the current basically flows along straight sections of silver, while in the transverse bridge, it is forced to ‘zig-zag’ in the silver between the filaments. As a result, the percolative trajectory of the current is longer in the transversal direction.

#### 3.2. $\langle E \rangle$ - $I$ curves

To further investigate the dissipative behavior of the samples the electrical field was measured as function of transport current passed along the two types of bridges. We let  $\langle E \rangle$  denote the average field between a pair of voltage contacts separated by a distance  $l$ , and use  $\langle E \rangle = V/l$  to determine it from the measured voltage drop,  $V$ .



**Figure 5.** (Upper) Volume fraction of superconducting material between voltage contact positions on a transverse bridge, whose positions are indicated by the dashed lines. (Middle) Proportion of superconducting material along the bridge.

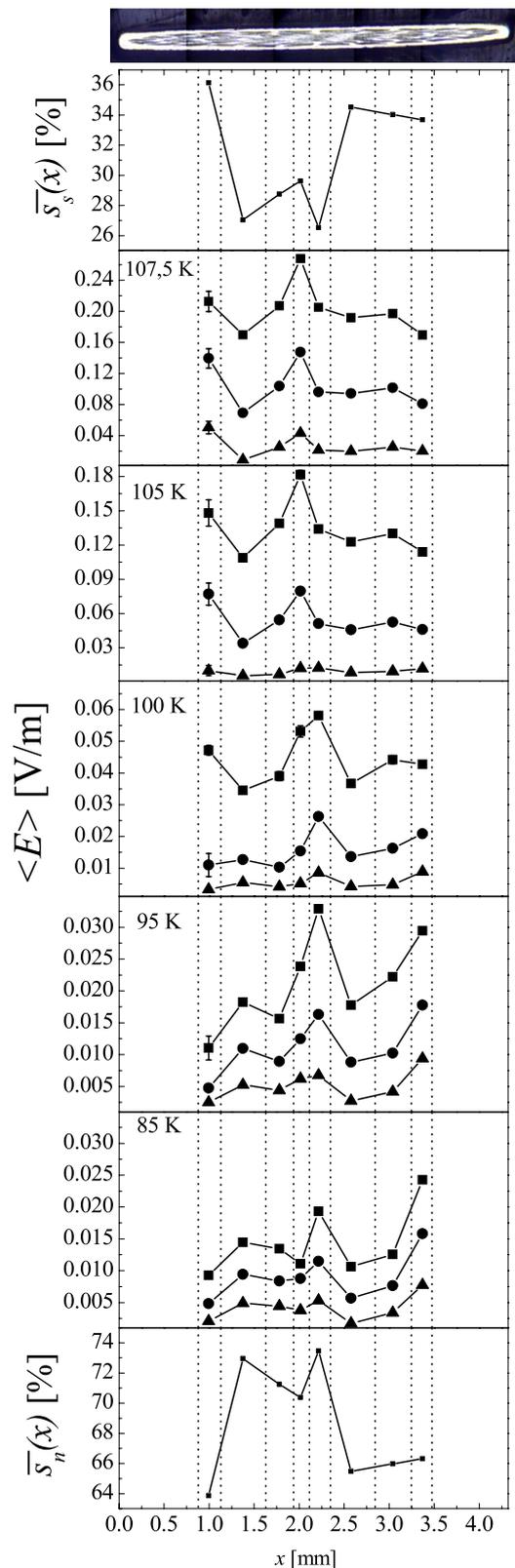
Figure 3 presents the  $\langle E \rangle$ - $I$  curves for a 6.2 mm long longitudinal bridge at different temperatures. The contacts were here placed at each end of the bridge. One can see that below  $T_c$ , there always exists a current interval where  $\langle E \rangle$  is essentially zero. Thus, we conclude that at sufficiently small currents there is no local dissipation anywhere along the longitudinal bridge.

For the transverse bridge the  $\langle E \rangle$ - $I$  curves are quite different. Figure 4(a) shows the behavior when the voltage contacts were placed at the ends of the bridge, which was 2.6 mm long. From the zoomed-in view in the inset one finds a finite slope in the curves even for very small currents. This means that there are essentially no superconducting paths along the transverse bridge. The current must pass, at least at some points, via non-superconducting phases in the filaments or flow via part of the silver matrix, in order to pass from one contact to the other.

The results shown in figure 4(b) reveal essentially the same behavior when the contacts are at the ends of a small segment of length  $l = 0.44$  mm located near the right end of the bridge. A different behavior, however, is seen in figure 4(c) when the contacts are at the ends of a segment near the central part of the tape. In that case, the inset shows, at least at some points, essentially no dissipation for currents below 100 mA at the lower temperatures. Thus, we find much stronger local variations in the dissipation for currents flowing transverse to the tape than for the longitudinal flow.

### 3.3. Morphology versus local dissipation

The bottom panel of figure 5 shows a metallographic image of the transverse section of the tape, already presented



**Figure 6.** Evolution of the local electrical field with the temperature along a transverse bridge, for current values of  $I = 0.5, 1.0, 1.5$  A (symbols correspond to the average field between two near voltage contacts, whose positions are indicated by the dashed lines). At the bottom and top we show the proportion of Ag and BSCCO, respectively, between the positions of voltage contacts.

in figure 1(a). It is safe to say that the proportion of superconducting material is constant in the longitudinal direction. However, the same cannot be said for the lateral direction of the tape. This is quantified in the intermediate panel, which displays the ratio,  $s_s(x)$ , of superconducting material (dark zones in the metallographic picture) to the total area of the tape, along its transverse direction. In the upper panel, we show a ‘coarser grained’ version of the same parameter,  $\overline{s_s}(x)$ , that has been constructed by calculating the proportion of filament areas taken from the figure at the bottom panel between different positions of the voltage contacts on the bridge we actually used for electrical measurements (indicated by discontinuous vertical lines). So,  $\overline{s_s}(x)$  is ideally suited for comparison with the dissipation profiles measured using those voltage positions.

Figure 6 shows the evolution of the local electrical field along the lateral bridge for several temperatures and three applied currents:  $I = 0.5$  A (triangles); 1.0 A (circles) and 1.5 A (squares).  $\overline{s_s}(x)$  and  $\overline{s_n}(x) = 1 - \overline{s_s}(x)$  dependences are shown at the top and bottom of the figure, respectively.

At 85 K, the local field follows quite closely the shape of  $\overline{s_n}(x)$ . However, as the temperature increases, dissipation follows the shape of  $\overline{s_s}(x)$  profile. A partial explanation of this phenomenon is the following: at low temperatures most filaments are in the superconducting state, so the silver is responsible for most of the dissipation: a higher local proportion of silver implies bigger local dissipation. However, as the temperature increases, more and more filaments undergo transition to the normal state. Since their resistivity is bigger than that of the silver at those temperatures, now the filament regions become responsible for most of the dissipation in the tape.

#### 4. Conclusion

We have been able to directly measure the transverse transport properties of Bi-2223/Ag multi-filamentary high temperature superconducting tapes, showing that there is always small nonzero dissipation in that direction for the whole bridge.

By means of submillimeter-resolved transport measurements, we have established the correlation between the transverse dissipation profile and the local superconductor to metal ratio in that direction. Our results demonstrate that, at low temperatures, the dissipation profile follows the distribution of silver but, as the temperature increases, it starts reflecting the distribution of Bi-2223. This is potentially relevant for AC applications, and also in a situation of failure due to transversal cracks, where currents are forced to flow perpendicular to the long direction of the tape.

#### Acknowledgments

A Borroto and L del Río contributed equally as first authors. We thank J Carrillo and G Sánchez-Colina for experimental help, Z Han for providing the superconducting tapes and A J Batista-Leyva for useful discussions. EA acknowledges support from the project ‘Complex Matter Science’ (Centre of Advanced Study at the Norwegian Academy of Sciences and

Letters, CAS), and the late M Álvarez-Ponte for inspiration. MA acknowledges FORDECYT program and COTACYT, Tamaulipas, Mexico for their financial support.

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