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Which kind of disorder most influences the magnetic properties of High-T_C Superconductors?

M. Bernaschi [a], A. Giannelli [b], C. Giovannella [c]

[a] IBM ECSEC Center, Via dell'Oceano Pacifico 171, Roma, Italia

[b] Sez. INFN, Universita' di Roma Tor Vergata
[c] Dip. di Fisica dell'Universita' di Roma Tor Vergata
Via della Ricerca Scientifica 1, 00133 Roma, Italia

Abstract

Josephson-Junction arrays are often used in computer simulations of the high-Tc granular superconductors. In order to take into realistic account the disorder intrinsic to those composite materials, a numerical study is presented of the effects of the three major disorder models for such arrays. The areal disorder turns out to be prominent in affecting the coherent behaviour of the superconducting networks, whereas the bond-dilution makes the magnetic hysteresis loop to shrink significantly.

High-T_C granular superconductors and high-T_C superconducting thin films can be both reasonably schematised, although on a different scale, through an ensemble of superconducting domains linked by junctions [1], of either Josephson- or proximity-effect type. The properties of the as-grown samples are often dominated by the behaviour of the intrinsically disordered junction network. As a consequence, the understanding of the role played by the *disorder* is of the uppermost relevance.

The *disorder* may indeed disturb and even destroy any possible *coherent* action of the junction network, in spite of the likely high usefulness of such coherence in some microwave-domain applications.

Disorder is intrinsic to the processes used in the sample fabrication, and may manifest itself as:

a) a distribution of the coupling strength, J, between the domains;

b) a random location of the superconducting grains respect to any possible regular geometrical network;

c) a lack of connections, when a superconducting grain is substituted by a void, or when the intergranular layer is too large.

To study the effect of the *disorder* on the superconducting networks we have first investigated the properties of an ordered 2D squared array of grains coupled via a superconducting junction network.
Then, we have introduced a controlled amount of disorder, and we have looked at the variations induced by the different kinds of disorder on the physical properties of the system. In particular, we have studied in detail the variations induced on the energy of the ground state of the system, E, and on its magnetisation, M. The computer simulations have been performed on a cluster of IBM RISC/6000 workstations. The hamiltonian of the junction arrays is, as usual, isomorphic to that used in describing the XY model in transverse magnetic field [2], i.e.

$$H = -J\ \Sigma_{ij}\ \cos(\phi_i - \phi_j + A_{ij})$$

where A_{ij} is the vector potential term, ϕ_i and ϕ_j are the phases characteristic of each single superconducting domain, and the sum is carried over the first nearest neighbours. All the approximations hindered behind the choice of that hamiltonian have been fully discussed in previous papers [3]. In order to better simulate the real

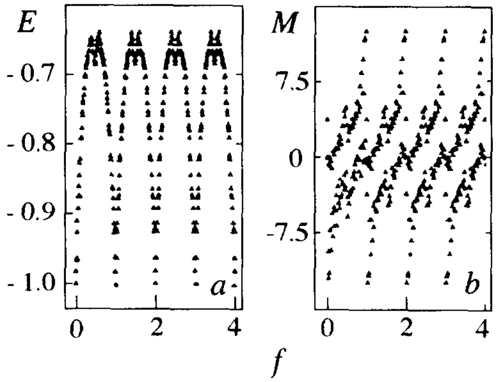

Fig. 1 a) Energy and b) Magnetisation loop for an ordered 16x16 array with free boundary conditions, as a function of the frustration.

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systems, free boundary conditions have been imposed.

As expected (see fig. 1), the properties of the ordered arrays turn out to be periodic in the value of the frustration, f (i.e. the transverse magnetic field, in fact $f = B \cdot a / \phi_0$ where B is the applied field, a the plaquette area and ϕ_0 the elemental quantum flux).

Before dealing with the effects of the disorder on the coherent properties of the arrays, let us show an explanatory example of what we intend for coherent action of a junction network. In fig. 2 we have reported, for three arrays of different sizes, the magnetisation normalised to the total number of the plaquettes vs. f. Note that the maximum value of M increases superlinearly with the size of the array: i.e. the response of the array to a magnetic field is greater than what is expected for an incoherent behaviour. Similar coherent effects have been observed in the case of the microwave emitting power of Josephson-Junction arrays of different sizes [4].

Let come back to the role played by the disorder. In the past, a few papers were published dealing with the problem of disorder [5]. However, it seems to us that their authors often chose unrealistic periodic boundary conditions. Moreover one could note a lack of comparative studies on the effects of the different kinds of disorder, and quite a scarce interest in the derivation of the magnetisation loops.

In this paper we have comparatively studied the effect provoked by three different disorders:

(i) the areal disorder, i.e. a distribution in the plaquette area, fig. 3;

(ii) the dilution disorder, i.e. a lack of some bonds (junctions) between grains, fig. 4;

(iii) the coupling disorder, i.e. a distribution in the coupling strength, J, characteristic of the junctions connecting any two superconducting domains.

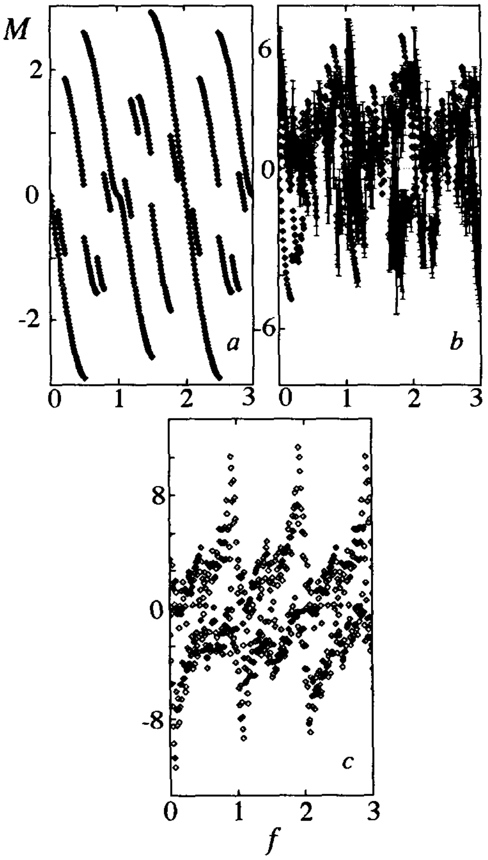

Figure 2. Normalised Magnetisation of arrays of different sizes: a) 2 x 16, b) 4 x 16, c) 8 x 16.

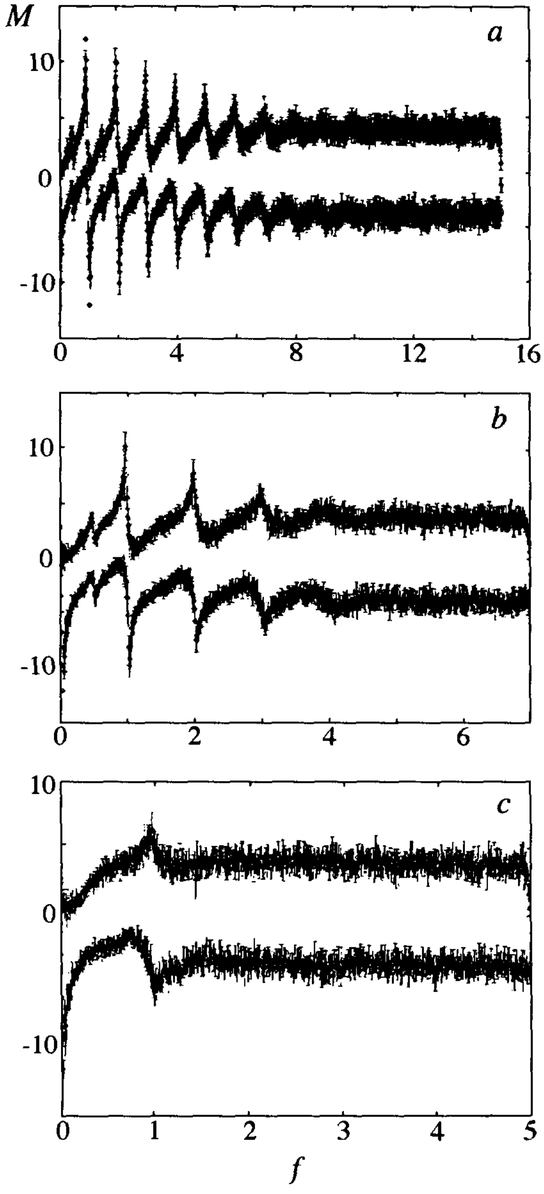

Figure 3. Magnetisation loop of arrays with a different degree of areal disorder caused by a random displacement, Δa, of the position of the superconducting domains respect to the lattice points: a) Δa = 0.05, b) Δa = 0.1, c) Δa = 0.3.

We would like to note that the choice of the above types of disorder has been dictated by the intent to simulate not only the effect of the intrinsic disorder on the properties of the as-grown samples, but also that of the disorder that would be introduced in a "perfect" sample, when one fabricates a junction- (or a wire-) array by means of lithographic processes.

The first evident result of the simulations is that the most disruptive action on the coherent effect is realised by the introduction of the areal disorder. The coherent response of the array as a function of f decays more and more steeply with the increasing value of Δa, see fig, 3. Beyond a certain value of f the junction array response to an increase of the value of the magnetic field is completely incoherent, and the value of the magnetic moment holds constant. For a quantitative discussion of this behaviour we refer the reader to the discussion presented by the authors in a recent paper to appear.

The bond dilution disorder, differently from the areal one, is not able to wash out the main coherent structures of the magnetisation loop even for p of the order or less than 0.7. On the other hand, the lack of bonds has another interesting effect that may help in explaining the shape of the experimentally measured hysteresis loops: it provokes a shrinkage of the loop. This effect is typically observed when one the measuring temperature is increased towards the critical one. Thus, one should conclude that the closing up of the cycle mirrors the breaking of the junction connections. However, as it can readily argued from fig. 2, the shrinking of the cycle is constant with the increasing value of f and is never complete. This phenomenon, in the present simulation, is mainly due to our neglection of any dependence of J on the magnetic field.

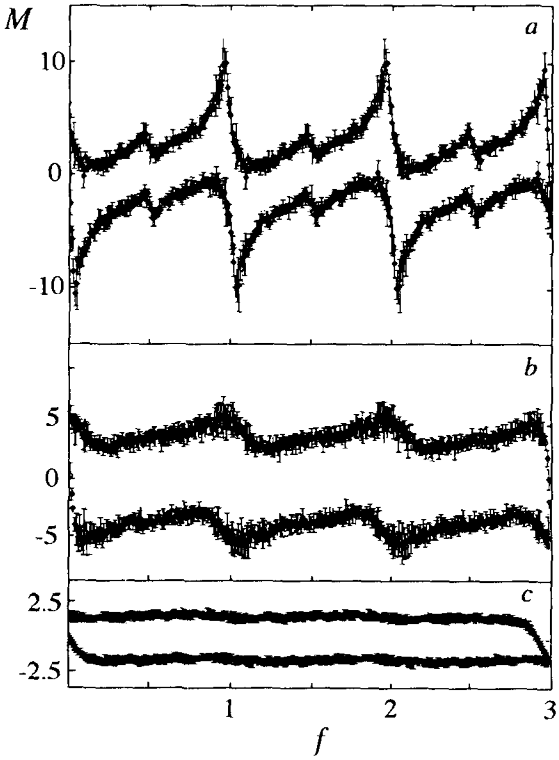

Figure 4. Magnetisation loop for 16x16 arrays with different degrees of bond dilution p : a) p = 0.98 (i.e. 2% of bond dilution); b) p = 0.8; c) p = 0.6.

One may suspect eventually that also a distribution of the J-values could affect substantially the properties of the array. However, preliminary results of simulations where J has been flatly distributed between 0.8 and 1 show a rather poor effect on the coherence of the array as well on the values of the physical quantities. This effect is not very dissimilar from what happens introducing a weak bond-dilution disorder. Since the shape of the magnetisation loop is not very much affected by the distribution of J, we show in fig. 5 the energy of the ground state, E, whose minima take, as expected, the value 0.9, i.e. the average of the J values. A quantitative analysis of the effects of the J distribution will be given in a forthcoming paper.

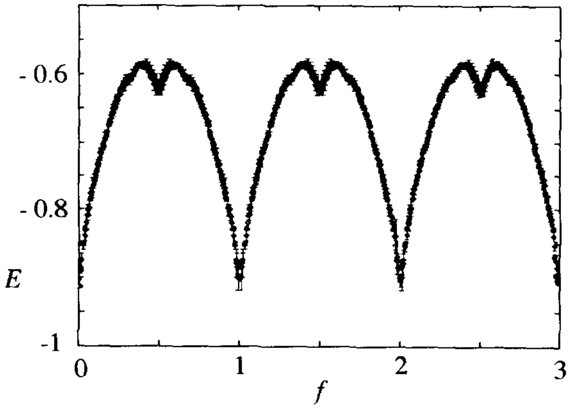

Figure 5. Energy of the ground state of a 16x16 array with the junction coupling strength, J, flatly distributed between 0.8 and 1.

In conclusion, from our simulations it seems that the coherent action of superconducting arrays of junctions (or wires) is mostly prevented by a random location of the superconducting domains. This suggests that in making artificial arrays by means of lithographic processes the definition of the plaquette area needs a tighter control than the constancy of the junction coupling strength.

The dependence of J on the magnetic field, together with the above elements, should be enough to describe the magnetic behaviour of real samples containing very many junctions.

On the viewpoint of the as-grown samples, the simulations seem to indicate that most of them contain a very high degree of areal disorder, probably not less than what has been used in the simulation of fig. 3c.

Certainly real samples present also a lack of intergranular bonds, whose number increases with the measuring temperature.

It would be very interesting to verify the above results in quantitative way on lithographically-made arrays: up to now similar measurements have not yet been realised, and this verification still lasts as a challenge for future experiments.

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