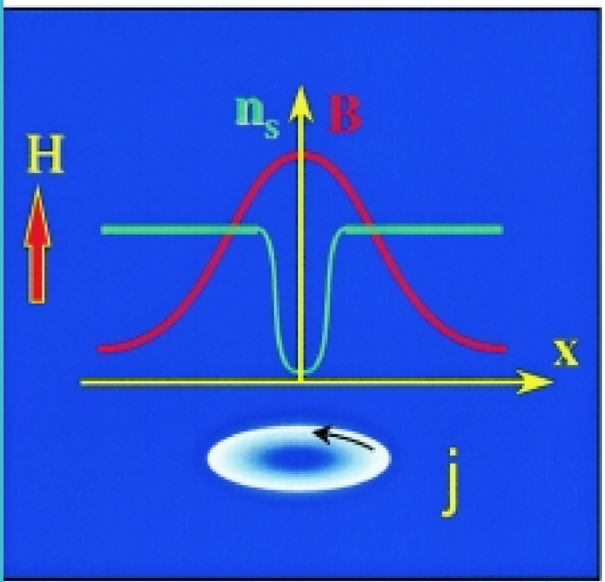
Vortex Matter in Superconductors at Extreme Scales and Conditions (VORTEX)

An ESF scientific programme



Extreme length scales (nano-engineered pinning arrays) and conditions (entangled flux lines, low temperatures, high magnetic fields, etc.) will be used to study systematically and to optimize the vortex confinement in superconductors, thus increasing their critical parameters (current and field) up to the theoretical limits.

The fundamental principles of the quantum design of these parameters will be worked out. Novel vortex phases, such as multiquanta and composite vortex lattices, vortex fluid coexisting with vortex solid, driven vortex lattices, entangled vortex matter, etc., will be studied experimentally by various vortex visualisation techniques, including STM, AFM, scanning Hall probe and SQUID microscopes, small angle neutron scattering, and modeled using modern theoretical and numerical techniques.

The fundamental research in the framework of this programme will form the basis of the advanced knowledge of the vortex matter in superconductors and will be also of importance for other scientific fields including superfluidity, turbulence, liquid crystals and plasma physics.

The European Science Foundation acts as a catalyst for the development of science by bringing together leading scientists and funding agencies to debate, plan and implement pan-European initiatives.

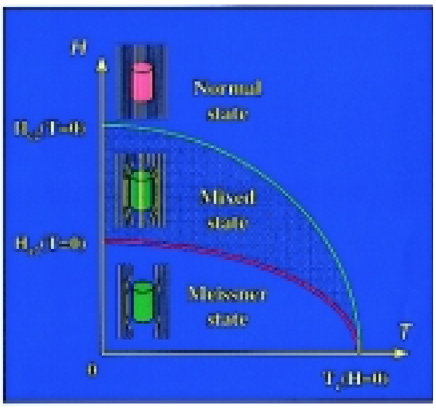


Fig. 2: Typical phase diagram for a type II superconductor. At low fields, in the Meissner state, no magnetic field can penetrate the superconductor. At intermediate fields in the mixed state, flux penetrates the superconductor as quantized flux lines, usually considered as line objects constituting the vortex matter. At high fields, superconductivity is destroyed and the normal state is recovered. © Vanacken

Introduction

Superconductivity is a remarkable quantum phenomenon which can be characterized by the coherence of the charged condensate over a macroscopic length scale. The absence of any resistance to the flow of the dc current and quantum coherence of the condensate make superconductors extremely promising materials for various applications in electrotechnics, micro-electronics, ultra-sensitive devices (field, current and voltage sensors, etc.) The possibilities of the practical applications of superconducting materials are determined by their critical parameters: temperature (T_c), field (H_c, H_{c1}, H_{c2}), and current (j_c) (see fig. 1). Therefore, besides the fundamental interest in superconductivity, there exists a strong demand from the modern technology to improve these critical parameters. The highest actual fields and currents have been realised in type-II superconductors in which the destructive action of the applied field H on singlet Cooper pairs, formed by electrons with opposite spins, results in the appearance of the quantized mixed state between the Meissner phase ($H < H_{c1}$) and the upper critical field (H_{c2}) (see fig. 2). In the mixed state the magnetic field penetrates the superconductor in the form of flux lines or vortices. Each flux line carries one flux quantum Φ_o and in a homogeneous superconductor these topological excitations arrange themselves into a triangular Abrikosov vortex lattice. The latter can be viewed as a lattice of rigid rods in low-Tc superconductors while in high-T_c cuprates and other quasi two-dimensional (2D) layered superconductors, due to strongly enhanced fluctuations, the vortices should be considered as a system of flexible interacting line objects generating a non-trivial statistical mechanics. This provides the basis for a *new state of matter*, usually referred to as "*vortex matter*" (see fig. 3).

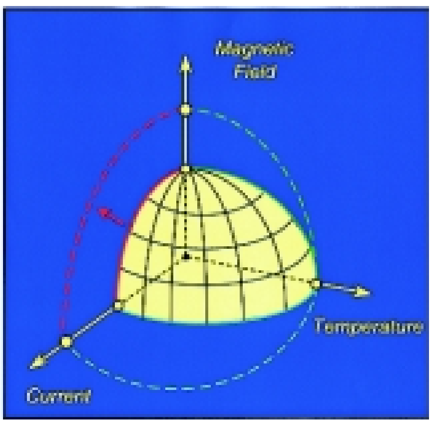


Fig. 1: Three dimensional phase diagram, showing the critical surface separating the superconducting and normal states. One of the objectives of this programme is to enhance critical currents and fields up to their theoretical limits (see red arrow). © Moshchalkov and Vanacken

Scientific background

Different phases of the vortex matter have been studied very intensively after the discovery of the high-T_c superconductivity. Vortex solids, such as lattices and glasses, can be moved under the influence of the Lorentz force. This leads to dissipation and under these conditions the critical current density is very low. Fluxon confinement ("pinning") prevents this motion and then j_c can be substantially increased. Therefore, for improving j_c, *the optimization of the pinning of vortices is the decisive factor.*

Since the vortex has a normal core with a size comparable to the superconducting coherence length, it is energetically favorable to superimpose the vortex cores spatially with normal state defects. Knowing that, intense efforts to optimize the vortex confinement by various defects have been made. As a rule in most cases a *random spatial distribution* of defects (impurity phases, voids, irradiation defects, etc.) with different sizes was used. (see fig. 3d). In this case neither the size nor the distribution of the pinning centers is properly controlled and the resulting pinning phenomena are very complicated and, in this case, *a disordered vortex matter* is stabilized by these random pinning arrays.

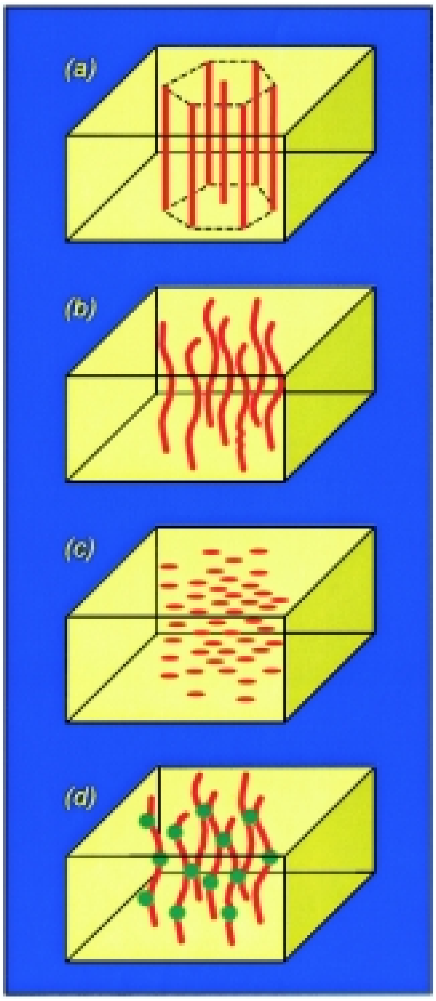


Fig. 3: Vortices in superconductors show a strong resemblance with ordinary matter: they can be in different aggregation states. In clean superconductors, at low temperatures, the vortices form a crystal-like solid (a). At higher temperatures the solid melts: vortices become flexible and mobile (b). In layered structures, the vortex is no longer a cylinder, but a staple of pancakes. At higher temperatures the staple ordering disappears, and the pancakes fall apart to form a gas (c). Defects in the crystal structure of the superconductor or impurities exhibit in general an attractive force on the vortices. They act as pinning centers. Since, in general, defects are randomly distributed, the ordering of the defects is also random. In the case that they are not mobile, one can speak of a vortex glass. © Kes

On the other hand, nano-engineered regular pinning arrays provide the unique opportunity to stabilize different types of flux line crystals (multiquanta vortex lattices, composite vortex crystals, etc).

A strong link between different European teams participating in this research already exists due to several European HCM/TMR networks, (the most relevant one is: "Flux Pinning in High Temperature Superconductors"), INTAS projects, and also through numerous bilateral programmes. The participating research teams from 10 countries have a recognized long standing expertise in superconductivity and the vortex matter. The research teams involved in this project have a wide variety of unique complementary techniques for the sample preparation and characterization. The collaboration in the framework of the ESF programme VORTEX will further strengthen the European leadership in this important field. In fact, the most spectacular discoveries in the field of the vortex matter and superconductivity have all been made in Europe: superconductivity (1911, H. Kamerlingh Onnes, the Netherlands), the Meissner effect (1933, W. Meissner and R. Ochsenfeld, Germany), the London equations (1935, F. and H. London, U.K.), the Ginzburg-Landau theory of superconductivity (1950, V.L. Ginzburg and L.D. Landau, Russia), the vortex state in type-II superconductors (1957, A.A. Abrikosov, Russia), the Josephson effect (1962, B.D. Josephson, UK), the magnetic decoration of the Abrikosov vortex lattice (1967, U.Essmann and H. Träuble, Germany), high-T_c superconductivity (1987, K.A. Müller and G. Bednorz, Switzerland). To keep this strong European leadership, the new coordinated research efforts, outlined in the VORTEX programme, are needed.

Aims and objectives

Recent spectacular progress in the fabrication of nanostructures and their regular arrays has given an access to a wide variety of *well controlled vortex confinement topologies* (including different *regular pinning arrays*) at extreme length scales, ranging from 1μm to 20 nm by photolithography and electron beam lithography, down to 0.1 nm by single atom manipulation. This progress has strongly stimulated the experimental and theoretical studies of nanostructured systems, including nanostructured superconductors (see fig. 4). In contrast to the classical approach, which relied upon the search for *new bulk materials* each time a specific combination of physical properties was required, the modern trend in condensed matter physics at the turn of this century is to *modify the properties of the same material through its nanostructuring and the optimization of the confinement potential and topology (concept of "quantum design"). One of the main objectives of this programme is to investigate the role of the vortex confinement by disordered and ordered pinning arrays in the evolution of the properties of the vortex matter at extreme length scales and conditions.*

The main envisaged achievement of the programme will be the (positive) answer to the following fundamental question: *Can the quantum design of the vortex confinement in superconductors result in the optimization of their critical currents and fields?*
By optimizing the vortex confinement, we shall be able to increase these two fundamental parameters of any given superconductor up to their theoretical limits.

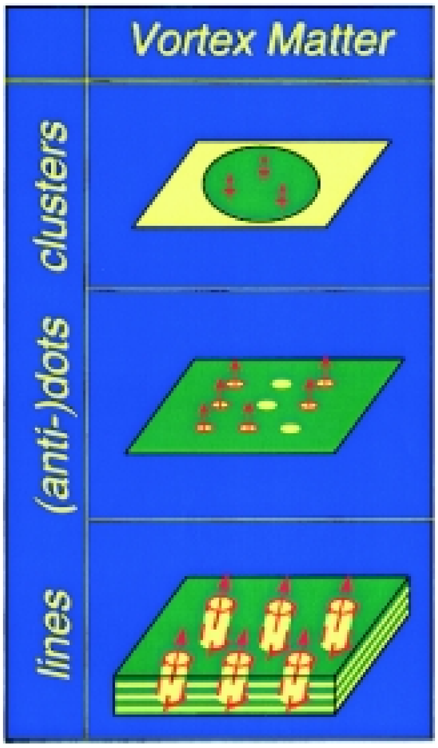


Fig. 4: Examples of nanostructured superconductors: clusters of vortices confined in a mesoscopic dot, regular square antidot array in a superconducting thin film, and regular arrays of line defects confining the flux. © Bruynseraede

The ESF programme

To study the evolution of the vortex matter at extreme length scales and conditions, and to fulfill the objectives of this programme, the research work will be focused on the following themes:

1. Novel vortex phases stabilized by regular pinning arrays of antidots or magnetic dots

The vortex phases to be studied are :

- multiquanta vortex lattices in single films and multilayers (see fig. 5)
- composite vortex lattices representing coexisting strongly and loosely bound vortices
- interstitial vortex liquid coexisting with vortex solid. The research efforts in the framework of this theme (both experimental and theoretical) are directed towards the *optimization of the pinning* in low and high T_c superconducting thin film structures by introducing artificial pinning arrays (e.g. magnetic dots and microholes "antidots")

2. Different forms of disordered vortex matter

Dynamics of elastic vortex lattices driven through random potentials is of great interest to other scientific disciplines, especially to those situated at the border line between condensed matter and statistical physics. The ideal model system in this case is the vortex lattice in presence of a random background of pinning centers. The relevant energy scales in superconductors can be easily changed by varying the experimental conditions such as temperature, magnetic field, anisotropy, and system size. Since global techniques, integrating response from huge vortex arrays, cannot provide sufficiently detailed information, it is quite interesting to see what can be done by directly probing the *local structural properties of static and moving vortex lattices and liquids*, using scanning SQUID, Hall and TM devices, magnetic decoration and SANS.

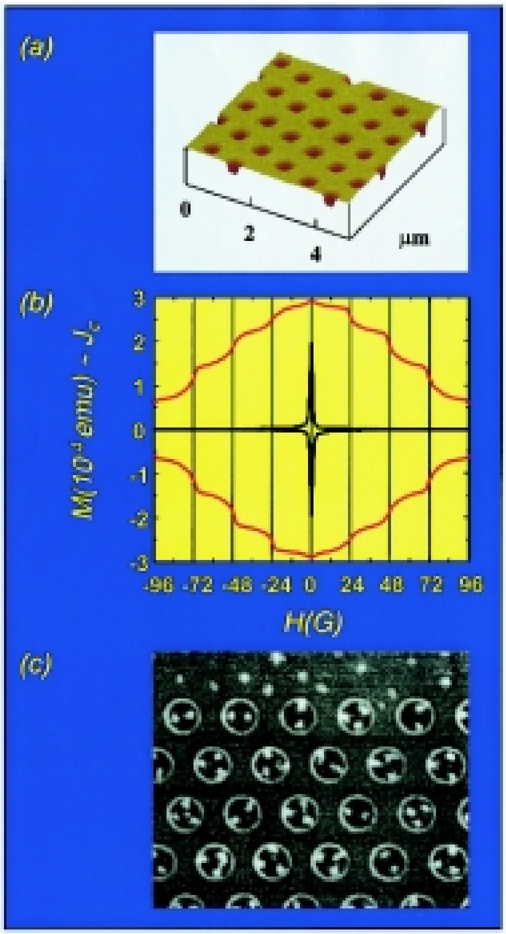


Fig. 5: Nano-engineered regular array of pinning centers (antidots) (a) . strongly enhance the critical current (b) and stabilize the multiquanta vortex state. (c) illustrates the coexistence of the $2\Phi_0$ and $3\Phi_0$ vortices between the second and third magnetic matching field. (a, b) © Moshchalkov, (c) © Pannetier, Bezryadin

3. The vortex matter composed from the Josephson vortices

Different forms of the vortex matter built up from the Josephson vortices will be investigated. Critical currents of sub-micron bridges and Josephson junctions employing high-Tc superconductors will be studied, aiming also at enhancements of critical currents in narrow superconductors. Networks consisting of regular arrays of superconducting rings and other mesoscopic plaquetts will be fabricated.

4. Vortex entry and vortex dynamics in individual singly - connected superconductors

The main idea here is to investigate the *topological and geometrical aspects of this problem.* These phenomena crucially depend on the topology of the problem, i.e., on the shape of the superconductor (long cylinder or slab, thin or thick disk or strip, rectangular platelet, etc., sphere, ellipsoid) defining the confinement of vortices and on the orientation of the applied magnetic field (parallel, perpendicular, oblique) and on the applied transport current.

5. Vortex matter at extreme conditions

Besides the vortex matter in superconductors, confined by nano-engineered regular and disordered pinning arrays, (extreme length scales) the programme also be focused on the properties of the vortex matter subjected to other extreme conditions and their combinations, such as:

- *extremely high magnetic fields*

Here the formation of multiquanta vortex lattices can be expected for certain classes of bulk superconductors. We intend to perform experimental and theoretical studies of superconductivity at very high DC and pulsed magnetic field: analysis of multi-quanta vortex formation and vortex lattice structure for this case; examination of cascade of transitions between different vortex structures in layered organic and high T_c superconductors in inclined magnetic field.

- *high temperature*

Here melting of the vortex glasses and vortex solids at temperatures approaching $T_c(H)$ will be investigated.

- *vortex matter with an extreme non-local elasticity*

Here we envisage the most pronounced effects in low dimensional superconductors. The knowledge of the elasticity of the vortex lattice in type II superconductors is crucial for most problems related to pinning of the vortex lattice and to thermal fluctuations and thermally activated depinning.

Activities

Workshops and Conferences

To explore the research frontiers and to evaluate progress in achieving the objectives of the project, workshops or conferences are foreseen (1 or 2 per year).

The first conference *Vortex Matter in Superconductors I* is on 18-24 September 1999 in Crete.

Short-Term Fellowships

To promote the mobility of young researchers short fellowships will be introduced. This will facilitate the access of partners to available complementary set-ups and to perform detailed studies of nano-engineered samples with controlled regular or disordered arrays of pinning centers by different techniques.

Short - Term Fellowships are intended for qualified young scientists (normally under the age of 35), who need further training and expertise in other experimental methods for a fruitful continuation and broadening of their research scopes. Applicants should hold at least a Master Degree/ Diploma. Short-term fellowships would facilitate the transfer of knowledge and techniques relevant to research from one laboratory within Europe to another (at least one contributing country should be involved). The fellowships are for a period of up to three months.

Selection rounds are *March 1, June 1, September 1 and December* 1 of each year.

Applications should reach ESF office prior to the corresponding date.

Monthly allowances will vary from 1067.1 EUR (FF 7.000) to 1372.0 EUR (FF 9.000) per month + a maximum contribution of 457.3 EUR (FF 3.000) towards travel (travel will be refunded on the basis of APEX type airfares or 2nd class train travel for shorter distances).

Grantees will be requested to provide a written report at the end of their fellowship. Travel costs and 75% of the allowance will be payable one month in advance; the remaining 25% will be paid one month after the termination of the fellowship, subject to receipt of the grantee's written report.

Short scientific visit grants

Contacts can be established and/or strengthened via individual short visits of researchers (up to two weeks). These visits are aimed at the optimum complementary use of the available experimental facilities and at a closer interaction between the experimentalists and theorists. Contacts should involve at least one participating country, and contacts within the same country will not be supported financially.

The maximum total amount granted (transport included) will be 762.25 EUR (FF 5 000). The actual reimbursement is defined by the ESF rules which can be obtained from the ESF secretary. There is *no deadline* for applications.

The criteria for eligibility and procedure for applying for one of these grants can be found on the programme's web page:
http://www.esf.org/VORTEX

Applications should be submitted (by post or email) to:

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For the latest information on this programme consult the VORTEX home pages:
http://www.esf.org/vortex *and* http://www.fys.kuleuven.ac.be/vortex/

Cover picture:
Vortex in a superconductor: schematic presentation of the superfluid density, n_s, field H, and supercurrent j. © Moshchalkov

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