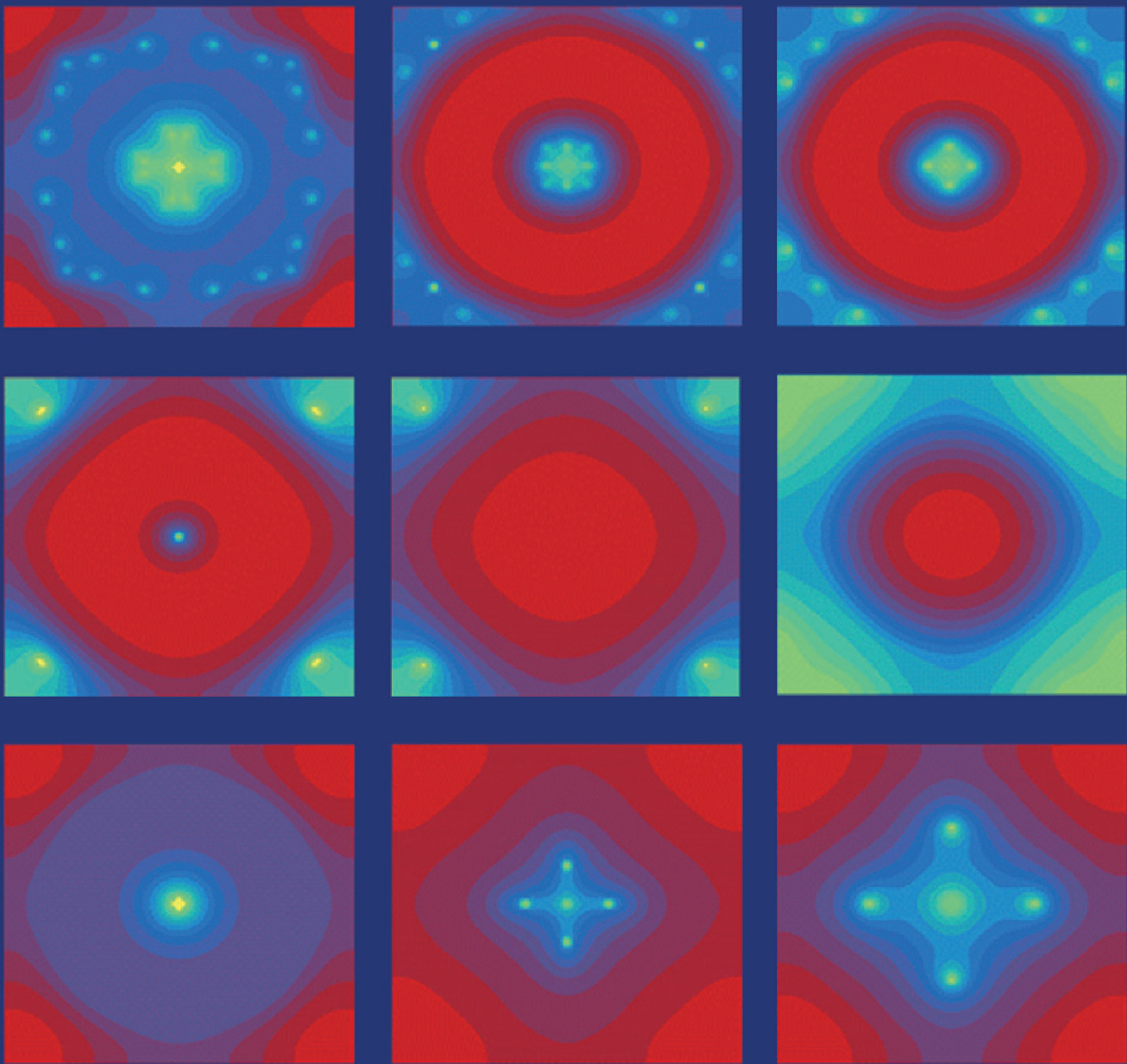
EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

RESEARCH NETWORKING PROGRAMME

NANOSCIENCE AND ENGINEERING IN SUPERCONDUCTIVITY (NES)

Standing Committee for Physical and Engineering Sciences (PESC)



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Cover picture:
Vortex patterns in a superconducting square with magnetic dot.
Courtesy of Victor V. Moshchalkov, Leuven.

Summary

Confined condensate and flux in superconductors will be investigated at nanoscale by using various confinement patterns introduced artificially in the form of individual nanocells, their clusters and huge arrays. The dependence of the quantisation effects on the confinement length scale and the geometry will be studied. The boundary conditions, defining the confinement potential, will be tuned by using the hybrid superconductor/normal and superconductor/magnet interfaces.

The evolution of superconductivity at nanoscale will be revealed by determining the size dependence of the superconducting critical temperature and the gap in mass selected clusters and nanograins and also by doing comparative studies of superfluidity in different restricted geometries.

Flux confinement by arrays of magnetic dipoles and other periodic pinning arrays in superconductors will be investigated. By tailoring the confinement, physical properties of the confined condensates and flux can be designed starting from the fundamental Ginzburg-Landau equations (including their generalisation to two component order parameters) and applying them to the real samples with the boundary conditions imposed at the physical sample's boundary.

This research will reveal the fundamental relations between quantised confined states and the physical properties of the superconducting quantum coherent systems, which will be also of importance for other scientific fields (superconducting elements for quantum computing, nanoelectronics, hydrodynamics, liquid crystals, plasmas).

The ESF-NES Programme and similar programmes in Japan and the USA together form the Global Research Networking, 'Nanoscience and Engineering in Superconductivity – NES'.

The running period of the ESF NES Research Networking Programme is for five years from May 2007 to May 2012.

Scientific Context

Nanoscale confinement phenomena have recently become the focus of modern condensed matter physics, and very intense research on confined condensates has already begun across the world. This brings us ***to the main objective*** of the proposed programme: **to investigate the effect of the nanoscale confinement of condensate and flux on superconductivity in order to reveal its nanoscale evolution and to determine the fundamental relations between quantised confined states and the physical properties of these systems, enabling 'quantum design' of their properties.**

Along the line of the main objective, the proposed research will be focused on the following topics:

- **Evolution of superconductivity at nanoscale, superfluidity in restricted geometries**

The correlation between the nanograin size and the superconducting gap and the critical temperature T_c will be investigated theoretically and experimentally. We will systematically reduce the characteristic size of superconducting grains and clusters in order to reveal the crossover between the bulk superconducting regime and the fluctuation-dominated superconductivity regime. For comparison, superfluidity in nanopores will also be studied as a function of the size of the nanopores.

- **Superconductivity in hybrid superconducting, normal (SN) and superconducting magnet (SM), nanosystems with tuneable boundary conditions**

Confined condensate will be studied in superconducting nano-islands surrounded by normal metallic or magnetic material. The role of proximity effects and the Andreev reflection in modifying the transparency of the sample boundaries will be revealed. The variation of the superfluid density near the boundary will be mapped by using the local scanning tunnelling spectroscopy (STS) techniques. Different vortex configurations, including those with symmetry-induced antivortices, and their dynamics will be investigated in individual nanostructures of different geometries. Here we expect to find the strong effect of the specific boundary conditions on confined flux and condensate.

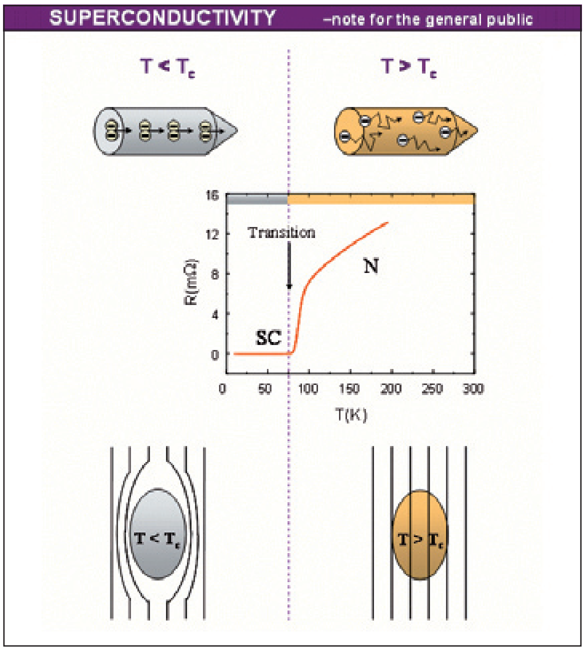


Figure 1: The superconducting ($T < T_c$) and normal state ($T > T_c$) of a superconductor. At high temperatures, the material is in the normal state (right side of the figure) and the carriers are scattered. As such, a resistance is observed as can be seen from the R vs. T curve (middle graph). Once the temperature drops below the critical temperature T_c, a transition to the superconducting state occurs. Instead of electrons, now the carriers become Cooper pairs. The resistance drops to zero, and simultaneously a diamagnetic state occurs. In this diamagnetic state, all magnetic field is expelled from the body of the superconductor as can be seen from the bottom left side of the picture.

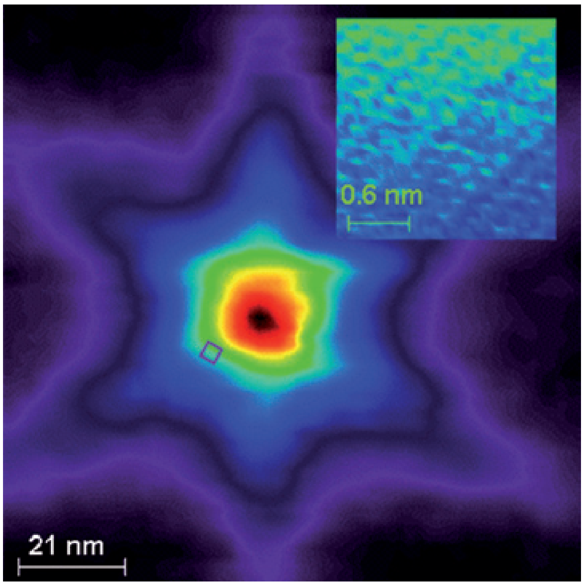


Figure 2: STM image of a vortex core in $NbSe_2$. The inset shows the underlying atomic wave density, visible in the vortex core (Courtesy of Hermann Suderow, Madrid).

- **Confined flux in nanostructured superconductors and hybrid SN and SM nanosystems**

Three different types of nanostructured superconductors will be investigated: individual nanocells of different topology, their clusters and huge arrays. By using local probe techniques, such as STM and the scanning Hall-probe microscope, the distributions of the order

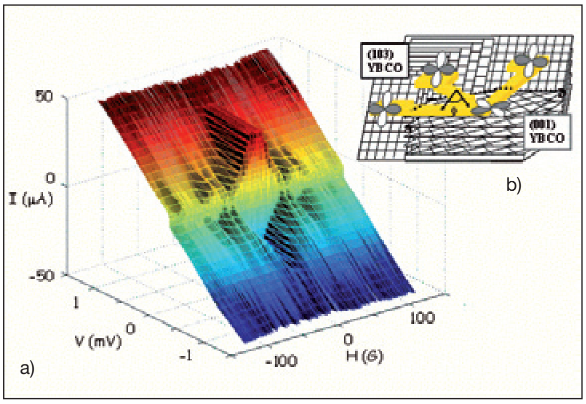


Figure 3: a) YBaCuO biepitaxial grain boundary Josephson junction as a function of the magnetic field (H). Measurements were taken at T=4.2 K and the interface angle orientation was θ=60°.
b) Scheme of the grain boundary biepitaxial junction. Different interface orientations can be selected through a suitable patterning of the seed layer (Courtesy of Francesco Tafuri, Naples).

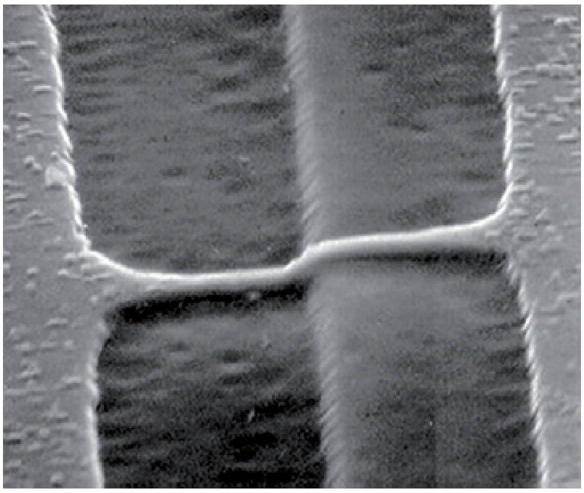


Figure 4: Nanoscale Y-Ba-Cu-O step-edge Josephson junction (Courtesy of R. Wördenweber, FZJ, Jülich).

parameter density and local magnetic fields will be mapped simultaneously and then compared with the calculations of these parameters based on the solution of the GL equations with the realistic boundary conditions imposed though nanostructuring. Hybrid SN and SM arrays will be also studied. Magnetic dots will be used to generate local vortex-antivortex dipole loops, which will be strongly interacting with the flux lines in superconductors, creating a tuneable magnetic periodic confinement. Different novel flux phases, including stable vortex-antivortex patterns, will be studied. Here we can anticipate a very interesting interplay between flux generated by an applied field and magnetic dipoles, which can substantially enhance flux pinning. Magnetic domains will be used to achieve vortex manipulation. Using the recent progress in nano-engineered pinning arrays in superconductors, similar structures can be made to confine flux in rotating superfluids. Keeping in mind that the coherence length for the ^{3}He superfluids is much longer than for ^{4}He, it seems to be much easier to fabricate periodic pinning arrays for ^{3}He. Instead of antidots used in superconductors, an adequate choice here is the periodic array of nanopillars. Here we expect to discover novel flux phases, which are otherwise not stable in a reference superfluid without a periodic pinning array.

- **Josephson effects and tunneling in weakly coupled condensates**

We shall investigate a variety of Josephson phenomena and phase shifting effects in coupled superconducting condensates, where nanoscale coupling can be provided through an insulating, metallic or magnetic layer. Hybrid structures are essential here in order to tune the coupling strength. These phenomena will be compared with Josephson effects in coupled superfluids.

- **Fundamentals of fluxonics, superconducting devices**

We will study the devices that control the motion of flux quanta in superconductors and could address a central problem in many superconducting devices; namely, the removal of trapped magnetic flux that produces noise. The controllable vortex motion will be used in nanostructured superconductors for making pumps, diodes and lenses of quantised magnetic flux. Vortex ratchets effects will be studied and then used to achieve vortex manipulation.

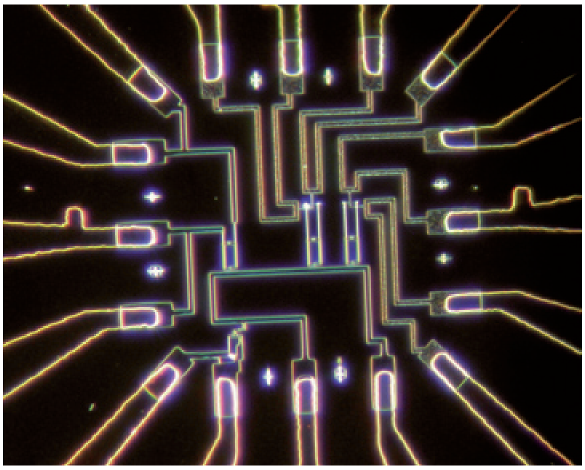


Figure 5: Superconducting Flux Qubit with Andreev read-out and antennae (Courtesy of V. Petrashov, London).

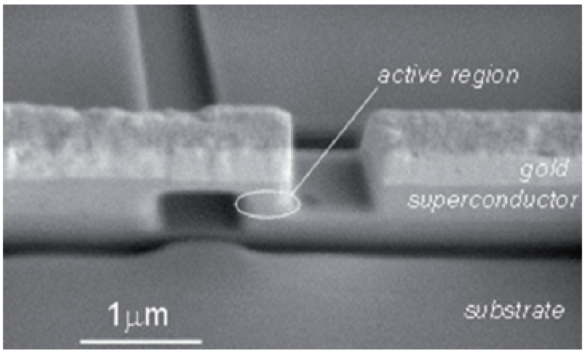


Figure 6: Nanoscale Josephson junction fabricated by focused ion beam (Courtesy of P. Warburton, University College, London).

One of the important aspects of this work is to investigate superconducting nanostructured materials for which the confinement of the condensate inside the samples can be controlled by imposing the proper boundary conditions for the order parameter at the nanofabricated boundaries. Remarkably, the order parameter, the analogue of the wave function for normal quantum mechanical systems, obeys the Ginzburg-Landau equations, which play a role similar to that of the Schrödinger equation. This gives a theoretical background for proving the feasibility of the fundamentals of the quantum design and nano-engineering of the superconducting critical parameters. The concept of quantum design is now the backbone for developing new elements and systems for microelectronics and information technology (quantum computing, SQUIDS with improved sensitivity, sensors, etc.).

Summarising the proposed tasks, the core of the NES – ESF project will be focused on the development of the fundamental principles of the 'quantum design' of the superconducting critical parameters through the optimisation of the flux and condensate confinement. The nanoscale evolution of superconductivity will be investigated. In individual superconducting nanostructures, topology- and geometry-dependent critical fields, as well as symmetry-induced antivortices in single and two-component order parameter systems will be investigated. In nanostructured superconductors a rich variety of novel flux phases and patterns will be studied in order to master vortex behaviour and develop fundamentals of fluxonics. Superconducting elements for quantum computing will be designed and investigated.

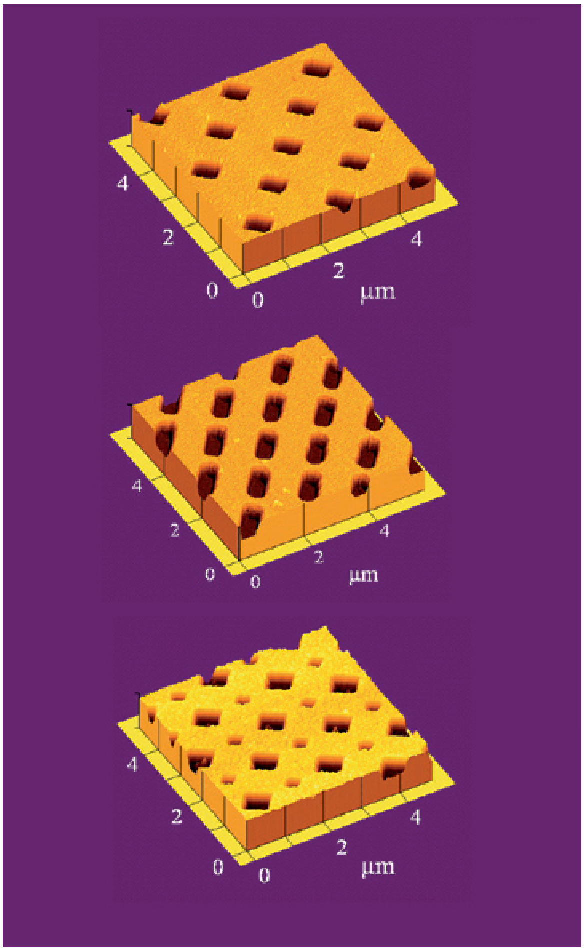
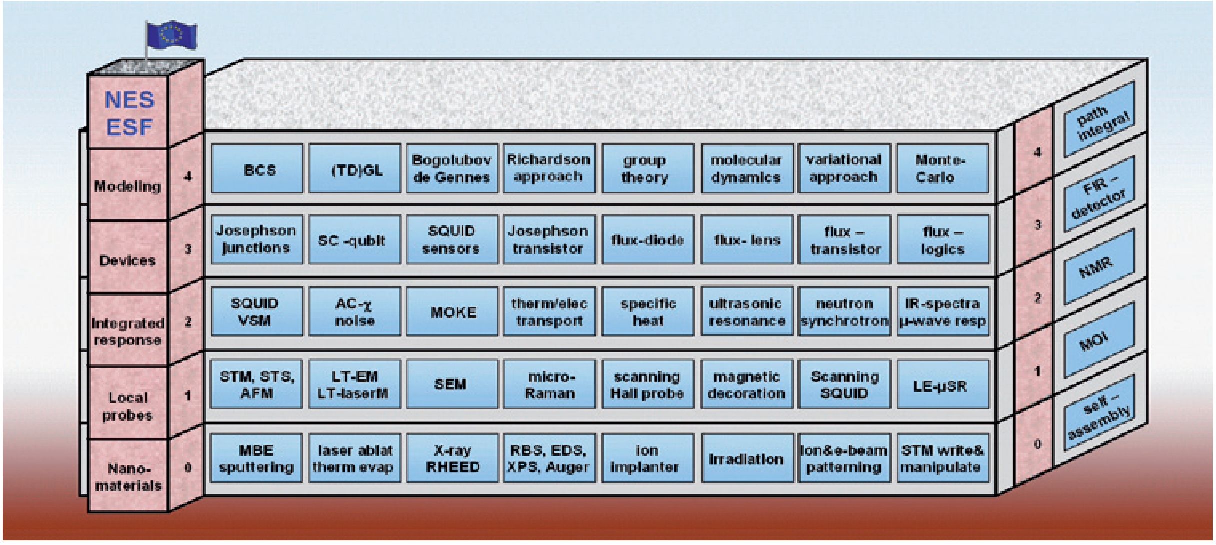


Figure 7: Nanostructured superconducting thin films produced by MBE and laterally structured via E-beam lithography.
This design of the antidot lattices allows controlled vortex pinning (Courtesy of Victor V. Moshchalkov, Leuven).

Facilities and expertise which will be accessible within the ESF-NES Programme



In order to successfully carry out the planned joint research, **the integration of the research facilities** of the NES teams will be achieved at five different levels via a European Virtual Institute (EVI):

- **Integration of modern sample preparation and nanostructuring techniques (level 0)**

Molecular Beam Epitaxy (MBE), Sputtering, Thermal evaporation, Laser ablation, Clean Room, Reflection High Energy Electron Diffraction (RHEED), Auger spectroscopy, Infrared Spectra, X-ray Photoelectron Spectroscopy (XPS), Energy Dispersive X-Ray Spectroscopy (EDS), Rutherford Backscattering Spectrometry (RBS), E-beam lithography, Ion beam etching, Scanning Tunnelling Microscopy (STM) writing, Bottom -up methods of self assembly, X-ray diffraction, Ion Implanter, Irradiation.

- **Integration of local probing techniques enabling vortex visualisation and condensate wave function mapping with a nanoscale resolution (first level)**

Local techniques are a key factor for achieving the scientific objectives, since these technologies provide an important microscopic information: (Low Temperature) STM, (Low Temperature) Scanning Tunnelling Spectroscopy (STS), Force Microscopy (FM), Low Temperature Laser Microscopy (LT laserM), Low Temperature Electron Microscopy (LTEM), Scanning Electron Micropscopy (SEM), Micro-Raman, Scanning Hall Probe or (array) Hall micro-magnetometry, Magnetic decoration, Scanning Superconducting Quantum Interference Device (Scanning SQUID), Magneto-Optical Imaging (MOI), Low energy muon spin rotation (LE-μSR), Transmission Electron Microscopy (TEM).

- **The next level of the shared research facilities is bulk integrated response (second level)**

The techniques needed for the experimental studies on nanostructured superconductors are:
SQUID, Vibrating Sample Magnetometry (VSM), Torque Magnetometry, AC-susceptibility, Noise measurements, MOKE, Thermal conductivity, Electrical transport measurements (including high frequency responses), Ultra Low Temperature Systems, Ultrasonic resonance, Specific heat, Neutron scattering, Synchrotron radiation, Far-infrared magneto-optics (FIR-MO), Nuclear Magnetic Resonance (NMR).

- **A test platform for the development of new applications (third level)**

Josephson junctions technology, Ultra sensitive SQUID magnetometers, Superconducting SC – qubits, flux –logics -lenses -diodes –transistors.

- **The theoretical methods and techniques will be integrated in order to interact continuously with the experimental NES teams (fourth level)**

The most important approaches describing the physics of individual nanostructured superconductors are:
Bardeen-Cooper and Schrieffer (BSC), (Time Dependent) Ginzburg-Landau (TD)GL, Bogolubov-de-Gennes, Richardson's approach to the solution of the BCS Hamiltonian, Molecular dynamics simulations, Group theory and Topology, Monte Carlo simulations, bosonisation, renormalisation group calculations, Keldysh-formalisms, Sine-Gordon-Equation.

Grants

The NES Programme supports two types of grants:

- **Short Visits** (There is no deadline for submitting such applications).
- **Exchange Grants:** Deadlines for submitting applications: 1 September, 1 December, 1 March, 1 June.
  All applications should be submitted via **the online application form** and using the guidelines:
  http://www.kuleuven.be/inpac/nes
  Priority will be given to applications where the institutions involved are in countries that financially support the programme.

Eligibility

- Undertake work applicable to the Programme.
- Apply to stay in a European country other than the country of origin.
- Return to the institute of origin upon termination, so that the applicant's institution may also benefit from the broadened knowledge of the scientist.
- Acknowledge ESF in publications resulting from the grantee's work in relation with the grant

Conferences and Workshops

Within NES, the following activities are planned:

- **NES Workshops** (at least one focused workshop per year) and Conferences (1st, 3rd and 5th year).
- Organisation of **Workshops/Conferences in a School format** thus giving an opportunity to young researchers and PhD students to learn efficiently about the main trends and the latest achievements.
- Organisation of **several Joint ESF-JSPS-USA events** with support from the JSPS and the USA for the participation of scientists from those countries in the NES-ESF events

For a regular update on these activities, please refer to our website: **http://www.kuleuven.be/inpac/nes**

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