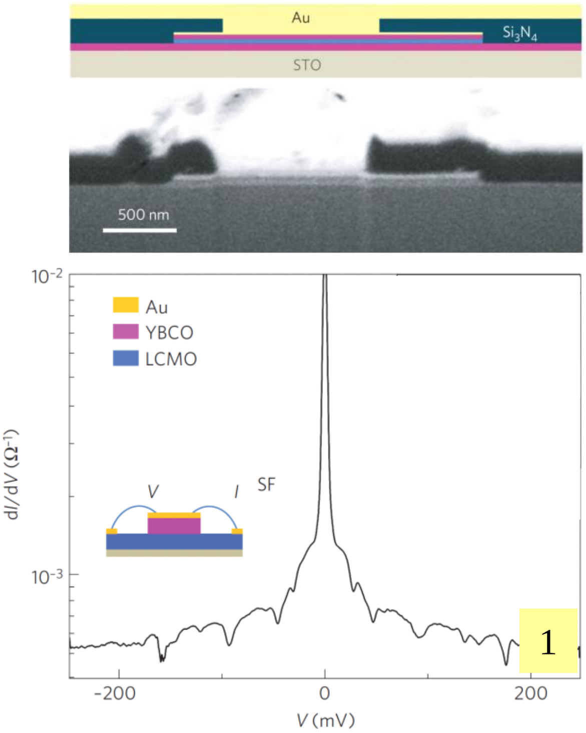
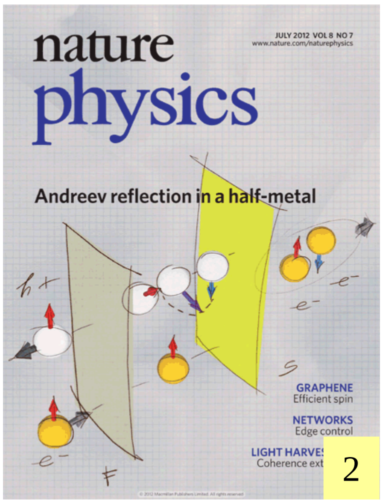
Marie Curie-FP7 “PIXIE” – Final report

In this report, the main results and ongoing developments of the project “PIXIE” are summarized. The project was aimed at experimentally investigate several aspects related to the study of spin transport and proximity effects at the interface between ferromagnets (F) and a high-T_c superconductor (HTCS); some of the mechanisms under investigation were unconventional pairing at F/HTCS interfaces, spin injection and relaxation in HTCS. We present below two different types of experiments designed to approach this problem. Some of the results achieved have been published (or submitted to publication) in international peer-reviewed journals and presented to international conferences.

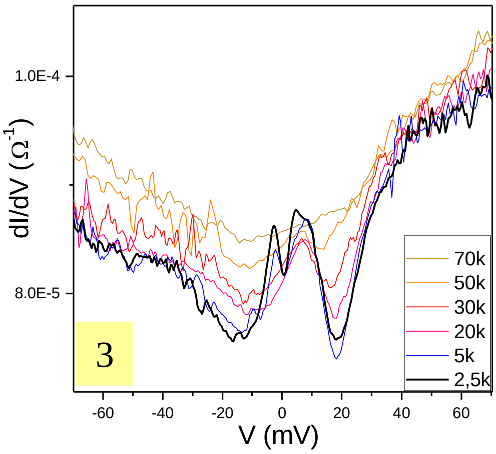
1. Spin triplet pairing nearby HTCS/F interfaces:



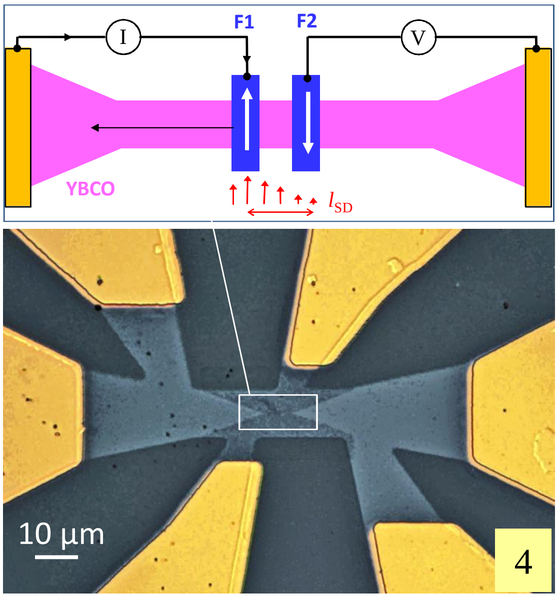
YBCO/LCMO. The objective of this investigation was to underpin the microscopic mechanisms of interaction between HTCS and half-metallic ferromagnets. Here, unconventional superconducting (triplet) pairing was predicted to appear in the ferromagnet, in contrast to the fact that the conventional Andreev reflection (responsible of the proximity effect) is forbidden. In our experiment we studied $YBa_2Cu_3O_7/La_{0.67}Ca_{0.33}MnO_3$ heterostructures in which the antagonistic nature of the electronic transport (superconducting on one side and 100% spin-polarized on the other) sets the ideal conditions for the observation of unconventional proximity effects. YBCO/LCMO and YBCO/LCMO/YBCO structures were grown by sputtering deposition; subsequently, vertical micrometer-size junctions of areas between 12 and 96μm^2 were fabricated through a series of steps including lithography, ion-etching, metal and insulator deposition (see a cross section of the junction in the top panel of Fig1). The transport properties of the junctions were studied through measurements of low-temperature differential conductance. Remarkably we observed oscillations in the differential conductance (see lower panel of Fig.1) as a function of the voltage bias produced by quasiparticle and electron interferences in the superconducting and ferromagnetic layers, respectively. These interferences imply Andreev-like reflections at the YBCO/LCMO interface and the coherent propagation of the resulting phase-conjugated quasiparticles through the entire YBCO and LCMO layers thickness. Because conventional (opposite-spin) Andreev mechanism is heavily suppressed in strongly polarized ferromagnets, the observation of the above effect implies the occurrence of equal-spin (triplet) Andreev reflection and provides a solid spectroscopic evidence for the long-range penetration of superconducting correlations into the half metallic ferromagnet. Results from this investigation have been published in *Nature Physics* and highlighted on the cover of the July 2012 issue (see Fig.2). Further results have been accepted for publication in the *European Physical Journal*.



YBCO/Co-Pt. Similarly to the previous case, vertical junctions have been fabricated using a Co/Pt multilayer instead of the half metallic manganite. It is known that for very thin layers of Co (*d*<3 nm) the magnetic anisotropy of the multilayer flips from in-plane to out-of-plane. It is therefore interesting to study the effect of in-plane versus out-of-plane magnetic domains on the spin transport through the YBCO/F interface in view of the possibility that magnetic-domain (or domain wall-) induced proximity effect may arise in these structures. Low temperature differential conductance measurements of YBCO/Co-Pt junctions showed a zero bias peak embedded in a gap-like feature(see Fig. 3). This may suggest the presence of Andreev bound states and hence the leak of superconductivity in the ferromagnet (proximity effect). The ongoing investigation is aimed at verifying the origin of this effect.



2. YBCO/ferromagnetic lateral spin valve. The aim of this experiment was to study the relaxation mechanisms by which a spin polarized current, injected into an YBCO strip, decays away from a ferromagnetic spin injector. The device designed for this purpose is a lateral spin-valve (see a sketch in the top panel of Fig. 4) in which two ferromagnetic elctrodes (injector and detector) are placed on top of the superconducting strip at a distance less than the spin diffusion length (l_{SD}). Because this lenght has been predicted to be in the range of 100-200 nm, the lateral size of both the superconducting and ferromagnetic elements must be reduced to the nanometer scale to avoid depolarizing effect. In view of that, micrometer-size YBCO bridges, realized by standard optical lithography, have been subsequently patterned to reach a final widht of 300 nm using a combination of e-beam lithography and ion-irradiation (see lower panel of Fig. 4). The optimization of the nanobridge properties and the realization of the ferromagnetic electrodes is currently under way.



The ferromagnetic electrodes were proposed to be made of Co/Pt multilayers. The thickness dependent magnetic anisotropy of this material may have important consequences in the switching mechanism of our device. We therefore investigated the properties of the ferromagnetic material more carefully by performing a study of the mixed-state magnetotransport properties of YBCO thin films combined with a Co/Pt multilayer with perpendicular magnetic anisotropy. Notably, we observed that depending on the direction of the external magnetic field, a pronounced decrease or increase of the mixed-state resistance is observed as magnetization reversal occures within the Co/Pt multilayer (see top panel of Fig. 5). Through a combination of different techniques (magnetic force microscopy, magnetostatic calculation, anomalous Hall effect and current-dependent transport measurements) we demonstrated that the resistance switching is connected to vortex dynamics effects induced by the stray fields. In particular, we can achieve a magnetic history–dependent pinning of vortices by properly manipulating the ferromagnetic domain state of the sample (see bottom panels of Fig. 5). This result, reported on *Physical review B*, provides valuable information on the interplay between the magnetic state of the Co/Pt multilayer and the superconducting properties of the YBCO film, and have to be considered during the optimization process of the lateral spin valve and eventually in the interpretation of the data.