ESRF	**Experiment title:** **High resolution resonant inelastic soft x-ray scattering for the study of magnetic and orbital excitations in 3*d* transition metal oxides**	**Experiment number**: HE2802
Beamline: ID08	**Dates of experiment**: LONG TERM PROJECT 25/2/09 – 3/3/09, 24/2/10 – 4/3/10, 16/6/10 – 22/6/10, 1/9/10 – 7/9/10, 1/6/11 – 7/6/11, 16/11/11 – 22/11/11	**Date of report**: 31/1/2012
Shifts: 18+18+18+ 18+18+18	**Local contact(s)**: N.B. Brookes	*Received at ESRF:*

Names and affiliations of applicants (* indicates experimentalists):

- * **Giacomo GHIRINGHELLI, Politecnico di Milano, Italy**
  * Giuseppe BALESTRINO, Roma Tor Vergata, Italy
  * Valentina Bisogni, ESRF
  * Lucio BRAICOVICH, Politecnico di Milano, Italy
  * Nicholas BROOKES, ESRF
  * Claudia DALLERA, Politecnico di Milano, Italy
  * Marco MORETTI, Politecnico di Milano, Italy
  * Ruggero VAGLIO, Università Federico II, Napoli, Italy
  Researchers not in the list of original applicants:
  * Matteo MINOLA, Politecnico di Milano, Italy
  * Gabriella DE LUCA, CNR-INFM Coherentia, Napoli, Italy
  * Marco SALLUZZO, CNR-INFM Coherentia, Napoli, Italy
  * Claudio MAZZOLI, Politecnico di Milano, Italy
  Luuk AMENT, Univ. Leiden, Netherland
  Jeroen VAN DEN BRINK**,** Univ. Leiden, Netherland

FINAL REPORT:

This document covers the three years of acivity.

INTRODUCTION

This LTP is the continuation of HE1952 long term project and is intended for the development of high resolution RIXS in the soft x rays used to study the magnetic and electronic properties 3*d* transition metal oxides with strong electronic correlation. In particular cuprates and manganites have been selected for the interest of their transport and magnetic properties. RIXS is a powerful tool to study simultaneously the magnetic and electronic excitations: *dd* excitations have usually local character, but magnons have collective nature and their dispersion is of high interest. We have recently demonstrated that the dispersion of single and multiple magnon excitations can be mapped in cuprates with Cu L_3 RIXS [1,2]. Very high resolution is mandatory for

that type of experiments, so the LTP is also meant to improve as much as possible the performances of the RIXS instrumentation available at ID08. Also when working at the oxygen K edge it is possible to measure multi-magnon excitations and the LTP is meant to first work at the O edge (530 eV), where the absolute combined resolution is better than at Cu L_3 (930 eV).
Due to practical reasons (see below) the present project has only started at the end of February 2009 and it has thus come to an end in November 2011 with the last run

YEAR 1 and 2 MILESTONES, and CHANGE in the TECHNICAL WORK STRATEGY

The original plan for the first two years had the following milestones:

Year 1

Technical

Refinement of the new refocusing system and, possibly, installation of the new grating holder.

Scientific

By exploiting the new refocusing system, which should impact mainly on the low energy range, studies of bimagnon excited at the O K edge (good candidates LSCO, CCO, NCCO); comparison to the results obtained at the Cu L_3 edge, probably to be repeated to exploit the improved energy resolution

Year 2

Technical

Final implementation of the singe photon counting with CCD

Scientific

Extension of the work on bimangnons in cuprates (Cu L_3 and O K edges) to other compounds, like the YBCO and BSCCO families. The use of O K edge data will have to be verified: the presence of a great number of inequivalent oxygen sites could complicate considerably the interpretation. Mn L3 edge RIXS of Manganites (see above).

As a matter of fact the new refocusing system had been already put into operation in 2008 at the end of HE1952, so the first milestone for Year 1 has been reached in advance. The scientific plan was to study bi-magnons in LCO and other undoped cuprates by O K edge RIXS. This was made easier by the refocusing optics, which was expected to improve the count rate especially in the low energy range of the spectrometer. The experiments were actually made not only on undoped systems, but also on underdoped LSCO, a superconducting sample with Tc=20 K. See below for a quick presentation of the measured data.

In consideration of the remarkable results obtained at the ADRESS beam line of the Swiss Light Source with the SAXES spectrometer thanks to the excellent resolving power ($E/\Delta E$= 9,000 combined at Cu L_3), and of the decision by the ESRF to upgrade ID08 within 2013 with the goal of having an extremely high resolving power ($E/\Delta E$= 30,000 at the Cu L_3) in RIXS experiments, the technical part of the present LTP had to be changed since the approval of the LTP itself. It has been agreed with the beam line responsible Nick Brookes that the AXES spectrometer would greatly benefit from being relocated along the beam line. Until now it has been used in combination with the PoLIFEMo monochromator, especially designed to install AXES before the main beam line monochromator (Dragon). PoLIFEMo had recently become the main limiting factor for the improvement of resolving power in RIXS experiment at ID08, as it had been designed in 1995 for medium resolution only. Thus in January 2010 AXES has been displaced and installed at the end of the beam line. The Dragon monochromator can thus ensure higher resolving power on the incident beam and a much improved ease of use for external users. Moreover a new refocusing mirror, studied jointly by our group and the beam line staff, should provide a much smaller vertical and horizontal focus on the sample (passing from 20x500 micron^2 to 5x50 micron^2), thus leading to an improvement of the resolution of the spectrometer itself.
The combined instrumental line width was expected to pass from 450 meV in the old location to 200-250 meV at Cu L_3 in the new set up, i.e. roughly an improvement of a factor of 2. Intensity is expected to increase due to differences in the monochromator efficiency. We expect that the ESRF spectrometer in the new setup is the best in terms of the product of resolving power and counting rate. Note that the line-width at the ADRESS beam line of the SLS (at Cu L_3) is 120-130 meV , which is by far the best worldwide; moreover 25-30 meV are the target of the new ID08 RIXS facility in a few years. It is thus clear that this intermediate intervention is meant to keep

AXES and ID08 competitive in the experiments limited by the counting rate (as it is often the case), while developing the new beam line.
The installation of the new refocusing mirror (toroidal, with sagittal focusing in the vertical direction) and of AXES (with modified measurement chamber) at 130° scattering angle (it was 110°) has been successfully completed in January 2010. The performances fully satisfy the original goals. The vertical width of focus on the sample, measured by scanning a razor blade attached to the sample holder, is ~5 micron FWHM. The combined resolution, in working conditions, i.e. with a reasonable counting rate, is 150 meV at O K, 190 meV at Mn L_3 and 250 meV a Cu L_3. These figures are a great improvement with respect to the previous situation and are less than a factor 2 worse than SAXES at the ADRESS beam line of the SLS.
We mention also that in 2008 the CCD detector had been changed. The new detector has a 2048x2048 pixel array and is liquid nitrogen cooled, for lower background signal, finer sampling and wider energy range with respect to the previous one (512x2018 pixels, Peltier cooled).
Finally an important technical work is going on to commission a multilayer mirror on AXES, which introduces an (optional) sensitivity to the polarization of the radiation detected by the spectrometer. In collaboration with the staff of ID08 the exit arm of AXES has been modified so that a B4C/W plane mirror (grown at the ESRF) can deviate horizontally the beam by about 45 degrees, thus introducing a non negligible differential transmission for the vertical and horizontal components of the polarization. The mechanical and vacuum components were installed in May 2011. The first tests, done in the last LTP run of June 2011, were successful thus making possible the first RIXS experiments with polarization analysis in the soft x-ray range. Based on the first tests, in Spetember and October 2011 a dedicated graded multilayer was produced by Christian Morawe (ESRF) and installed on AXES. In the LTP run of November 2011 the new set up was commissioned and spectra of underdoped YBCO6.6 were measured with the polarimeter.

We summarize below the work done in the 6 runs of the LTP. The main subject (high resolution RIXS of cuprates, at O K and Cu L_3 edges) has been realized, together with major technical improvements. Some strategic choices have been somehow modified to avoid overlap or competition with the work done by us at the ADRESS beam line of the SLS.

(25/2-3/3 2009, 18 shifts) - OXYGEN K EDGE RIXS: RESULTS on LCO and LSCO

In the first run we have measured the O K edge RIXS spectra of LCO and LSCO. The samples were thin films (100 nm thick) grown on $SrTiO_3$ and $LaAlO_3$. The intensity of the signal was very low because the RIXS cross sections are quite small at the oxygen K edge and the beam line and spectrometer are less efficient at 530 eV than at 930 eV. The combined line-width (typically 180 meV) was tuned to compromise with the counting rate and each spectrum results from a total accumulation of several partial measurements up to a total of 6 to 10 hours.
As in the intermediate state the O 1s core hole has no spin-orbit interaction the single magnon excitations are forbidden in the RIXS process. So the only contributions to the spectra below 0.6 eV is coming from bi-magnons, i.e., couples of interacting mangnons, similarly to what happens in optical Raman measurements but adding the possibility of studying the dependence on q along about 1/3 of the Brillouin zone. In the undoped sample we have found that the bi-magnon peak does not disperse in the reciprocal space in agreement with theoretical calculations made with the Ultrashort Core-hole Life-time model [3], and it is due to the weighted mapping of the bi-magnon DOS made by Oxygen-RIXS. This mapping is different from the Cu-L_3 mapping which shows dispersion. In the superconducting LSCO sample the magnetic excitations are still present in the spectra, despite the fact that the long range antiferromagnetic order is destroyed by hole-doping. Both in undoped and in doped systems the magnetic excitations are seen only if the incident photon energy is properly chosen. A summary of the results is shown in figure 1 (undoped LCO) and in Fig. 2 (doped LCO with 8% holes)
A manuscript is in preparation presenting a subset of these data together with data measured at the Cu K and Cu L_3 edges [4]. Another manuscript in preparation [5] will present the data on the doped LSCO compounds. The publication of these data has been unfortunately delayed by the moving of the first author (V. Bisogni) from

ESRF to IFW Dresden in 2010, but we expect to submit within March 2012 the two papers to PRB for a joint publication. The data are still very original and worth getting published in Phys Rev. B.

(24/2 – 4/3 2010) COMMISSIONING OF THE NEW SETUP

At the end of February 2010 we have made the commissioning of the new toroidal refocusing mirror dedicated to the RIXS end station and of the AXES spectrometer in the new position. The targeted performances in terms of beam spot size on the sample and of combined energy resolution in the RIXS experiment have been fully reached. In particular:

1. The new toroidal refocusing mirror in combination with the bendable (variable curvature) mirror after the monochromator exit slit, produces a 60 micron (horizontal) × 5 micron (vertical) FWHM spot on the sample. The spot has been measured first by imaging with a lens and a CCD camera the visible light generated on a phosphor screen: this gave the shape and the horizontal size. Then in the vertical direction the width was measured by scanning a razor blade mounted on the sample manipulator (recently motorized on the vertical motion) and by taking the derivative of the drain current signal from the blade itself. The depth of focus appears to be sufficient for the experimental constraints (several mm), largely due to the intrinsic depth of focus of the Dragon monochromator itself, whose exit slit is the optical source for the refocusing mirrors.
2. The 5 micron vertical width of the beam focus on the sample (to be compared to ~20 micron in the previous set-up before the Dragon and to 20 to 100 micron of the older set-up with no refocusing optics), allows us to use the AXES spectrometer in a slit-less mode, thus gaining a considerable factor in throughput.
3. The 5 micron spot optical source for the AXES grating (compared to 10-15 micron of the entrance slit in the previous setup) allows a considerable gain in resolving power of the spectrometer itself. We estimate <u>the linewidth of the spectrometer itself</u> to be 60 meV at Ti L_3 (460 eV), 100 meV at Mn L_3 (640 eV) and 170 mV at Cu L_3 (930 eV).
4. We have made intensity and resolution tests at 4 energies Ti L_3 (460 eV), O K (530 eV), Mn L_3 (640 eV) and Cu L_3 (930 eV). The gain in intensity with respect to the previous setup has been considerable, mainly at the lower energies. At O and Mn we estimate that, as comparable combined resolving power almost an order of magnitude has been gained in intensity on the AXES detector. This is obtained thanks to the good focalization of the sample and to the fact that with the PoLiFEMo monochromator the insufficient cooling of the grating was forcing us to use only one undulator and to shorten the footprint on the grating itself.
5. We have also gained in ultimate combined resolving power: if one can afford closing very much the slits of the Dragon monochromator (down to 5 micron) the combined linewidth can now range from 130 meV at Ti and O, 160 meV at Mn and 210 meV at Cu. These liewidths increase by 20% in working conditions, where a higher count rate is needed. We notice that these values are less than a factor of two worse than at the SLS – where the spectrometer is twice as long.
6. Two examples of spectra are given in the figures below for Mn in MnO, a good benchmark for *dd* excitation spectra, and Cu in insulating NdBCO film, a YBCO like sample.

(16/6 – 22/6 2010) COMPLETION of COMMISSIONING and of OXYGEN K EDGE RIXS on LSCO

In this run the beam time was devoted to finishing the commissioning of the spectrometer and refocusing mirrors at various energies (Cu L_3, Mn L_3, O K), after the work done in February. And to original measurements on LCO at the O K edge.

Commissioning. We checked for the best combination of grating and slits opening (in the Dragon monochromator) to obtain good resolution while keeping a reasonable count rate. Due to some problems in the general alignment of the beam line we could not fully retrieve some of the performances already obtained previously in February and, later, in September. However the tests were very useful and confirmed the improvement in the performances (resolution and count rate) obtained by placing AXES pas the Dragon.

Experiment. The original measurements were made on a film of $BiMnO_3$, at the Mn L_3 edge, to make a test in view of future experiments in collaboration with M. Salluzzo from Napoli; and on a freshly prepared LCO film (on STO), at the O K edge, to confirm and conclude the experiments made previously (in 2009). In consideration of the low count rate we measured only 4 cases: two at the Γ point, two at the maximum reachable $q_{//}$ along the $(\pi,0)$ and the (π,π) directions. The data are presented in figure 5 and are the experimental basis for an article to be submitted shortly by V. Bisogni [4]. These results are the first study of bi-magnon excitations by O K edge RIXS. The combined experimental resolution is about 150 meV.

(1/9 – 7/9 2010) MAGNON DISPERSION in CCO, LCO THIN FILMS and CCO/STO SUPERLATTICES MEASURED with Cu L_3 RIXS

In this run we eventually exploited fully the new performances of AXES at the end of the beam line. The overall alignment of the beam line itself had been better optimized with respect to the previous experiment in June, and both intensity and resolution have been better in September. We worked at the Cu L_3 edge and optimized performances there.

We first solved some technical issues. The razor blade used to evaluate the vertical focus at the sample position was found to have been damaged in the previous experiment; we found that it degrades very fast under the beam: the same position along the cutting edge cannot be use more than 10 times without degrading the sharpness, and to obtain reproducible results we have to periodically move laterally the blade to use "fresh" regions that have not been damaged by the beam yet. We found a good stability of the focus position and size over days. We implemented a new sample holder allowing the manual rotation (by a wobble stick in the preparation chamber) of the sample around an axis perpendicular to the sample surface. Thanks to the better resolution of the spectra we could improve the procedure used to obtain the spectra from the raw images recorded by the CCD detector. In particular we have better defined the iso-energy line shape (approximated very well by 2^{nd} degree polynomial law) and the broad background due to the diffused scattering at the grating surface. This background is approximated by the sum of two Lorentzian curves proportional to the integral of the measured spectrum.

Then we performed original measurements on thin films of cuprates. In particular we measured, with ~250 meV resolution combined):

- The magnon dispersion in La_2CuO_4 (LCO, 100 nm thick film on STO) along the $(0,0) – (\pi,0)$ direction, as a cross check with previous measurements done at SLS on another (older) sample.
- The magnon dispersion in LCO almost along the magnetic Brillouin zone boundary (BZB), i.e., along a circle at constant q// and variable azimuthal direction, thanks to the new sample holder. In this way we could measure the dispersion along the BZB, previously observed in LCO with inelastic neutron scattering and in Sr_2CuOCl_2 by RIXS (at the SLS). In our measurements the "phi-scan" was done for the first time in soft-RIXS.
- The magnon dispersion in $CaCuO_2$/STO (CCO, 14.5 nm thick), the infinite layer cuprate.
- The magnon dispersion in $(CaCuO_2)_n/(STO)_m$ superlattices, with $n\times m = 2\times2, 3\times3$, along the $(0,0) – (\pi,0)$ direction.

The experimental resolution and the count rate allowed us to derive the magnon dispersion in these samples, although it is somehow more difficult to obtain than at the SLS. In figures 6 and 7 we show the final results for the magnon dispersion along the BZB and a comparison of the superlattices with the pure CCO film. These results are of high importance for two reasons. First, they demonstrate that magnon dispersion in layered cuprates can be studied at ID08 already today, making AXES the only possible alternative to SAXES of the SLS for this class of measurements. Second, the difference found between CCO/STO superlattices and pure CCO is a novel result *per se*, leading interesting information on the magnetism of CCO at the interface with an insulating material. In particular we observed magnon dispersions in superlattices consistent with a super-

exchange slightly reduced with respect to bulk CCO but still comparable to that typical of cuprates. The results are also supported by fittings based on the linear spin wave theory (see fig. 7). In connection with these findings, it must be noted that these superlattices (prepared in Roma Tor Vergata by D. Di Castro and G. Balestrino) are very unique in showing metallic conductivity although obtained from two insulating compounds. Moreover very recently Di Castro *et al.* reported that if grown in a highly oxidizing atmosphere these CCO/STO superlattices are superconductors with a maximum T_c of 50 K. The results on the previous non-superconducting superlattices have been submitted to Phys. Rev. B in Dec 2011; reports from referee are positive and we are confident that it will be accepted shortly [6].

(1/6 – 7/6 2011) POLARIZATION ANALYSIS OF THE SCATTERED X-RAYS IN Cu L_3 RIXS

In this run the beam time was mainly devoted to the commissioning of prototype polarimeter mounted on AXES to analyze the polarization of the scattered beam. It was installed on AXES at the end of May 2011 and featured in the ESRF website "spotlight on science" of 6/9/2011. This prototype is designed to work at the Cu L_3 edge and it is based on a W/B_4C multilayer mirror operated at a 40˚ total deflection angle (not far from the ideal value dictated by the competition of polarisation sensitivity and intensity), so that the reflectivity of the σ component is larger than that of the π component (from Fresnel laws, $R_\pi/R_\sigma \approx \cos^2 2\theta$). The multilayer is installed in the output arm of AXES, i.e. past the grating analyser, without any degradation of the *combined* resolving power $E/\Delta E \approx 3000$, which is identical with and without the polarimeter.

The first experiments exploiting the new linear polarization analysis were made on the infinite layer $CaCuO_2$. By using both σ and π incident polarization at Cu L_3 edge, and by collecting polarization dependent spectra, 4 spectra were obtained, allowing the linear polarization properties of the scattered photons to be determined. From a theoretical point of view it is well known that a spin flip must be accompanied by a rotation of the linear polarization vector of the scattered photon. Similarly a *dd* excitation corresponding to a transition from the ground state with the 3d hole having x^2-y^2 symmetry to an excited state of *xy* symmetry is expected to belong to a crossed polarization channel, i.e. for an incoming photon with π (σ) polarization a photon with σ (π) polarization goes out. For undoped $CaCuO_2$ the raw data are shown in fig. 8. The decomposition of the spectrum with π incidence, integrated over the two grey regions, is represented by the bars in the lower panels. Clearly the main peak (1.9 eV) is dominated by the crossed polarisation channel πσ. The theoretical weights of the πσ and ππ components (bars without filling) obtained from a single ion model for the x^2-y^2 to *xy* excitation [7] agree well with the experimental finding. This new approach is also of great importance for the study of low energy magnetic excitations, as shown in fig. 8c. Within the statistical uncertainty, the ππ component vanishes not only at the main single-magnon peak at ~0.2 eV, as expected from theory, but also at larger energy transfer, indicating that higher order terms also belong to the πσ crossed polarization channel. This discovery is of great help for the interpretation of RIXS intensities in magnon spectroscopy. In particular in doped cuprates, where magnon-like excitations survive at least up to optimal doping with considerable spectral weight [8], it will be possible to disentangle the evolution of the charge contribution from the spin one, allowing in the future to give an absolute value of the magnetic intensity – and therefore of the spin susceptibility - measured in the RIXS experiments and hopefully to get an even deeper insight into the high T_c physics.

(161 –22/11 2011) POLARIZATION ANALYSIS OF THE SCATTERED X-RAYS IN Cu L_3 RIXS

In this last run the polarimeter was improved thanks to a new dedicated multilayer mirror, with graded period increase the angular acceptance. A new commissioning was needed as many modifications had been made to the mechanics and to the optics. The final result was a gain of the efficiency by a factor 2 to 3 with respect to the first set up. Still one has to accumulate for several hours (6 to 8) to get a reasonable statistics on spectra that can be measured in 1 hour with our polarimeter. But this is already enough to allow a complete polarization dependence in selected cases. .

After a full characterization of the system using CCO/STO superlattices we have worked on a YBCO6.6 crystal. Spectra were taken with and without polarimeter with both H and V incident polarizations. Having previously measured the reflectivity of the multilayer mirror for both polarization components, it was then possible to decompose the RIXS spectra into the contributions from the two scattered photon polarizations. An example is

given in Fig 9, where in the low energy scale the single magnon contribution (crossed polarizations) is well separated from the charge excitations and the bi-magnons. Also the for dd spectrum we gain insight thanks to the polarimeter: the relatively broad dd excitation peak gets separated in the xy component (mainly crossed polarization) at 1.5 eV and in a broad and intense feature, originated from other dd excitations together with a strong charge excitation continuum. This is the very first experiment of polarized RIXS in the soft x-rays and it demonstrate that the polarimeter can be really used to resolve ambiguous assignements in the spectra, mainly when spectra are intrinsically broad and a better energy resoluton can provide little impact.
During this run we have also taken some data on the charge modulation in YBCO. This charge modulation gives a very weak Brag incommensurate peak around 0.31 rlu. This peak is hardly visible with energy integrating sample. But by extracting the elastic signa from RIXS spectra allowed us to document the effect. In this run we explored the incident photon energy dependence of the incommensurate peak on the underdoped YBCO6.6 crystal. These data are going to complete a set of data showing for the first time the presence of approx period 3a charge stripes in YBCO, a work initially conducted at the SLS, then at ESRF and finally at the soft x-ray diffractometer at Bessy [9]

PERSPECTIVES

The upgrade of AXES has been very successful. Obviously the performances of ADRESS at the SLS are still out of reach with the present apparatus, but the gap has been greatly decreased. AXES at ID08 is by far the best instrument for soft x-ray RIXS operating worldwide (apart from the SLS, and waiting to see how the new AERHA RIXS station will work at SOLEIL). Moreover the combination of high energy resolution and polarization analysis makes RIXS with AXES at ID08 unique. Until now in fact the polarization of scattered photons had never been measured in RIXS experiments in the soft X-ray range due to technical difficulties, contrary to the hard X-ray regime where the experimental feasibility has already been proven [10]. AXES will allow to perform a variety of very interesting experiments, mainly based on the accurate observation of the *dd* excitation spectrum in correlated systems and in the determination of single magnon or bi-magnon dispersion in judiciously chosen cuprate samples. Besides the additional selectivity on the polarization of scattered x-rays will be useful in assigning spectral features, while waiting for the next generation of instrumentation to be installed at ID08.
Although a large fraction of the beam time has been devoted to technical work (commissioning), we have collected valuable original data too. Part of them is already included in references [4,5,6,7,9]. Other will be published later. We underline the fact that the technical work is extremely valuable because it profits to all the RIXS experiments made at ID08 in this period. Having a state of the art RIXS apparatus at the ESRF even before the new beam line and spectrometer are realized is of great importance to build a solid user community in this field.

FIGURES

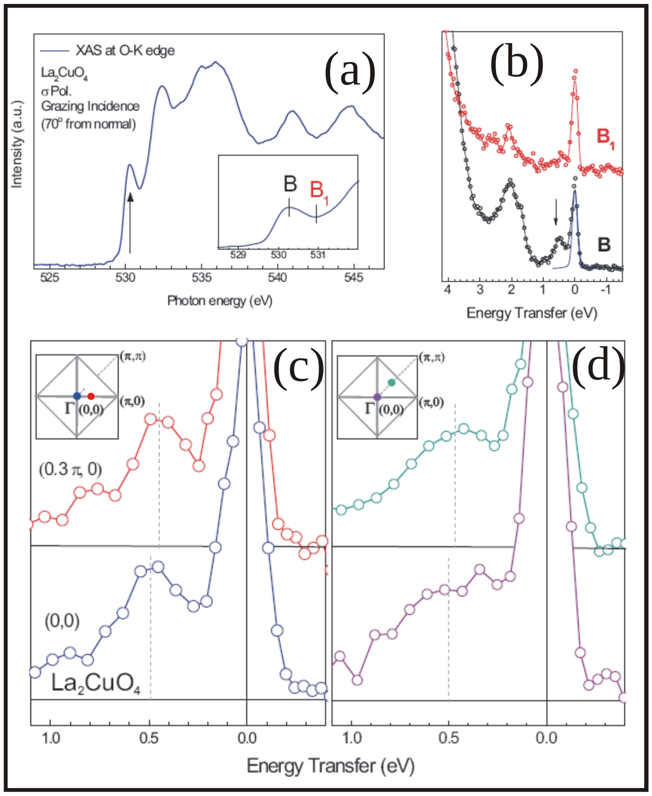

Figure 1
Examples of O K edge RIXS spectra measured on LCO.
Panel a: The O K edge XAS; the first peak indicated by the arrow was chosen for the RIXS measurements; it corresponds to excitations to the upper Hubbard band states, strongly hybridized with Cu 3d states.
Panel b: RIXS spectra taken at the main peak (B) and 0.7 eV above (B1); the former shows clearly both *dd* and magnetic excitations.
Panels c and d: the detail of magnetic excitations for different point in the reciprocal space.

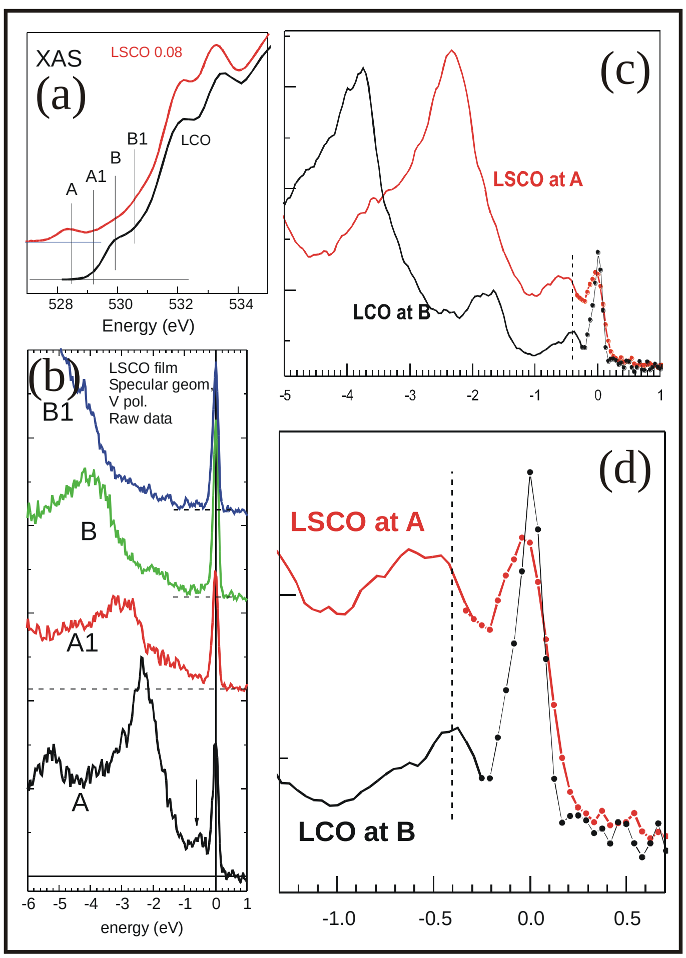

Figure 2
Examples of O K edge RIXS spectra measured on LSCO.
Panel a: The O K edge XAS and the excitation energies chosen for the RIXS measurements.
Panel b: the RIXS spectra at the 4 excitation energies.
Panels c and d: Comparison of LCO and LSCO RIXS spectra measured at the B and A excitation energies. The dd excitations, well seen in LCO around 1.8 eV, in LSCO are hardly distinguishable from the oxygen band fluorescence. The low energy excitations around 0.5 eV are very different in the two compounds too.

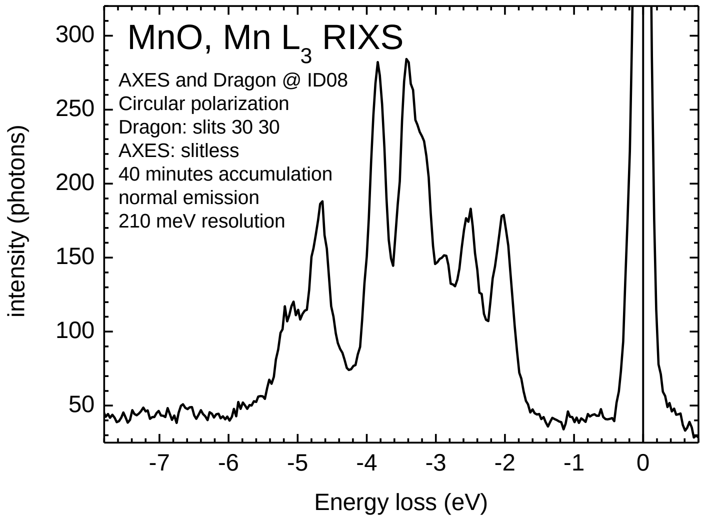

Figure 3
Example of a Mn L_3 RIXS spectrum measured with the new setup on MnO, using circularly polarized radiation. The data quality is comparable to that of spectra measured at ADRESS in the commissioning phase of the beam line [5].

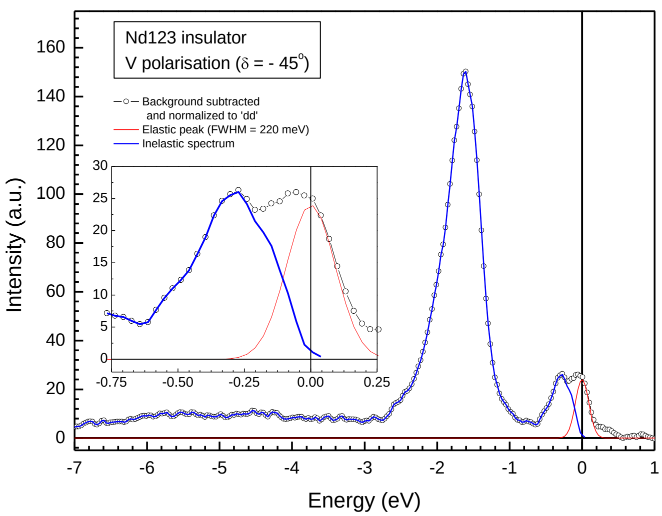

Figure 4
Example of a Cu L_3 RIXS spectrum measured with the new setup on NdBCO, using vertical linearly polarized radiation. The combined linewidth is around 210 meV, which allows us to resolve the single magnon excitations in the mid-IR region, i.e. below 0.5 eV energy loss.

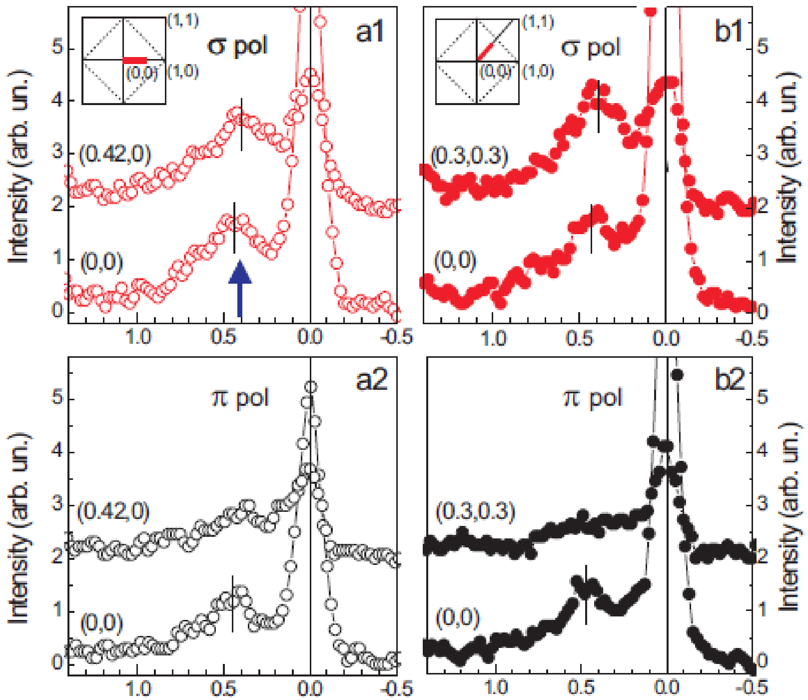

Figure 5
RIXS at the oxygen edge for LCO. Panels (a1) and (a2) present the experimental data measured along the direction from (0,0) to (1,0) (open symbols) with respectively σ (red) and π polarization (black); panels (b1) and (b2) refer to the direction from (0,0) to (1,1) (filled symbols) again with σ and π polarization.

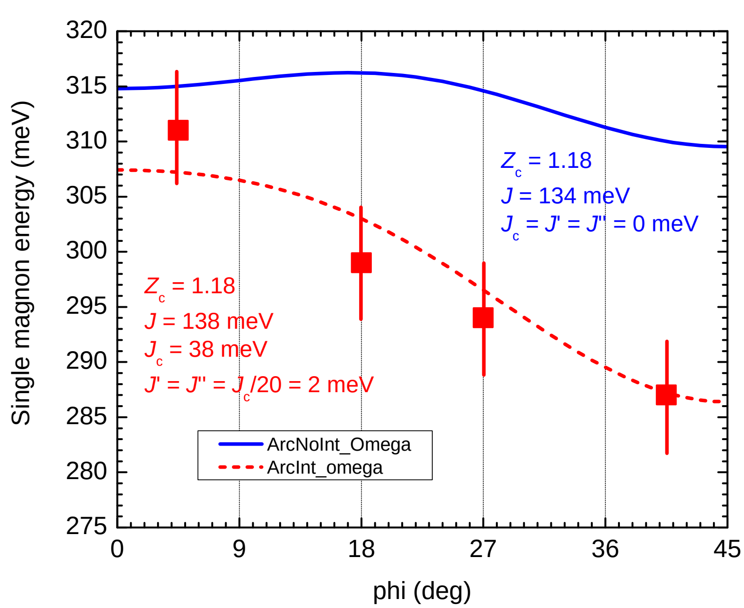

Figure 6
The single magnon dispersion along the Brillouin zone bounday in LCO as measured by Cu L_3 RIXS at ID08. The experimental points are compared with the theoretical behavior expected from the spin-wave theory and the parameters obtained from inelastic neutron scattering measurements [6].

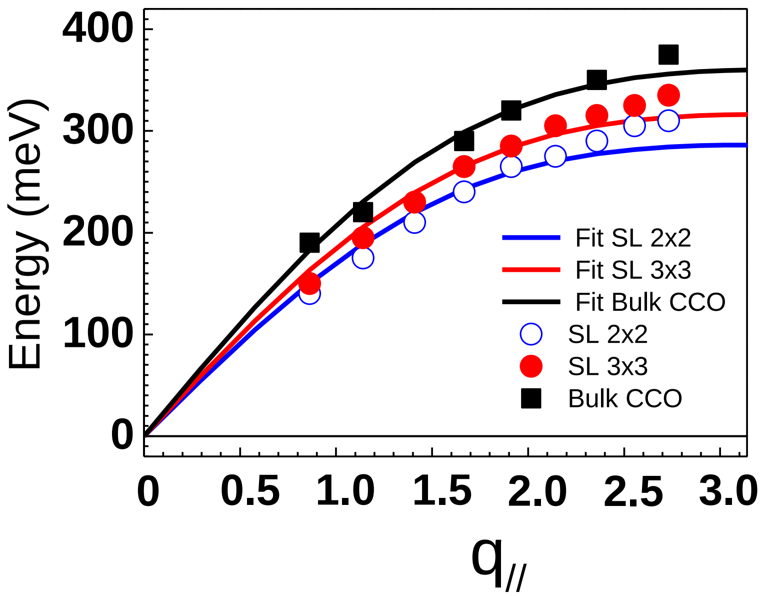

Figure 7
The single magnon dispersion in CCO (black filled squares) and CCO_n/STO_n superlattices with n=2 (blue open circles), n=3 (red full circles) as measured by Cu-L_3 RIXS at ID08. Solid lines with the same color code represent the relative fittings according to the linear spin wave theory. The magnon energy is slightly reduced when passing from bulk CCO to the superlattices.

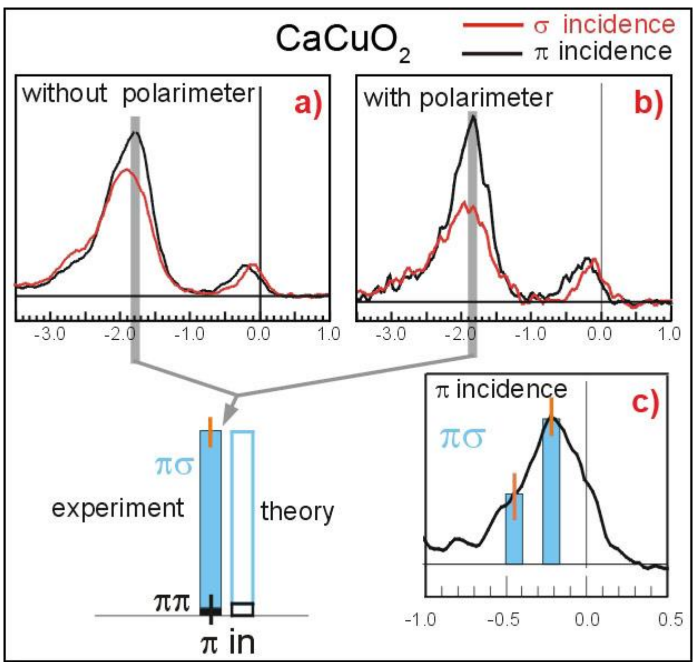

Figure 8
RIXS spectra of $CaCuO_2$ at $q \approx 0.25$ r.l.u. in the (1,0) direction, using σ (red) and π (black) incident polarisation. The spectra were measured a) without the polarimeter in the scattered beam, and b) with the polarimeter in the scattered beam. By combining the 4 spectra and using the known polarisation transmission factor, the 2 components of the scattered beam can be evaluated for π incident polarisation at the main *dd* excitation peak and at the magnetic peak. For the *dd* peak the experimental result is compared to the theoretical expectation for the x^2-y^2 to *xy* excitation. Panel c) see details in the text.

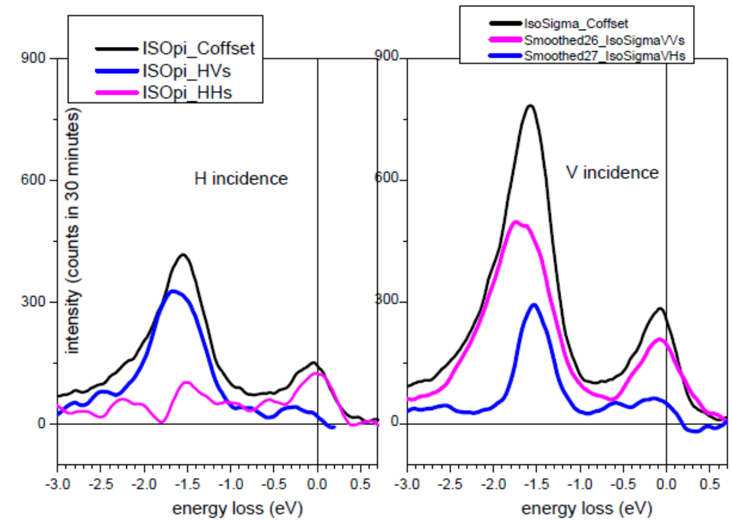

Figure 9
RIXS spectra of $YBa_2Cu_3O_{6.6}$ at $q \approx 0.25$ r.l.u. in the (1,0) direction, using V and H incident polarisation with and without the polarimeter in the scattered beam. They were then decomposed into the pure components (VV, VH, HV, HH) thanks to the knowledge of the polarization dependent reflectivity of the multilayer. The spectra shown here have been smoothed aftert the decomposition, to take away some residual oscillations coming fro the detector background signal and from some residual misalignments in the optical system. Wenotice however that it is possible to teak spectra with the polarimeter while keeping the 250 meV energy resolution.

REFERENCES

Refs. [4], [5], [6, [7], [9] make use of data acquired during the present project.

[1] L. Braicovich, L. J. P. Ament, V. Bisogni, F. Forte, C. Aruta, G. Balestrino, N. B. Brookes, G. M. De Luca, P. G. Medaglia, F. Miletto Granozio, M. Radovic, M. Salluzzo, J. van den Brink, and G. Ghiringhelli, Phys. Rev. Lett. **102**, 167401 (2009)

[2] L. Braicovich, J. van den Brink, V. Bisogni, M. Moretti Sala, L.J.P. Ament, N.B. Brookes, G.M. De Luca, M. Salluzzo, T. Schmitt, V.N. Strocov, and G. Ghiringhelli, Phys. Rev. Lett. **104** 077002 (2010).

[3] J. van den Brink, Europhys. Lett. **80**, 47003 (2007). F. Forte et al., Phys. Rev. B **77**, 134428 (2008).

[4] V. Bisogni, L. Simonelli, L. J. P. Ament, F. Forte, M. Moretti Sala, M. Minola, S. Huotari, J. van den Brink, G. Ghiringhelli, N.B. Brookes and L. Braicovich, to be submitted to Phys. Rev. B.

[5] V. Bisogni, A. Bendounan, N. B. Brookes, G. Ghiringhelli, M. Moretti Sala, and L. Braicovich, to be submitted to Phys. Rev. B.

[6] M. Minola, D. Di Castro, L. Braicovich, N.B. Brookes, D. Innocenti, M. Moretti Sala, A. Tebano, G. Balestrino, and G. Ghiringhelli, Phys. Rev. B**, under review**.

[7] M Moretti Sala, V Bisogni, C Aruta, G Balestrino, H Berger, N B Brookes, G M de Luca, D Di Castro, M Grioni, M Guarise, P G Medaglia, F Miletto Granozio, M Minola, P Perna, M Radovic, M Salluzzo, T Schmitt, K J Zhou, L Braicovich and G Ghiringhelli, New J. Phys. **13** 043026 (2011).

[8] M. Le Tacon, G. Ghiringhelli, J. Chaloupka, M. Moretti Sala, V Hinkov, M. W. Haverkort, M. Minola, M. Bakr, K. J. Zhou, S. Blanco-Canosa, C. Monney, Y. T. Song, G. L. Sun, C. T. Lin, G. M. De Luca, M. Salluzzo, G. Khaliullin, T. Schmitt, L. Braicovich and B. Keimer, Nature Physics 7, 725 (2011)

[9] G. Ghiringhelli, M. Le Tacon, M. Minola, C. Mazzoli, M. Moretti Sala, G.M. De Luca, M. Salluzzo, A. Frano, S. Blanco Canosa, E. Weschke, C.T. Lin, E Schierle, L. Braicovich, , and B. Keimer, tobe submitted to Science.

[10] K. Ishii, S. Ishihara, Y. Murakami, K. Ikeuchi, K. Kuzushita, T. Inami, K. Ohwada, M. Yoshida, I. Jarrige, N. Tatami, S. Niioka, D. Bizen, Y. Ando, J. Mizuki, S. Maekawa, and Y. Endoh, Phys. Rev B **83**, 241101(R) (2011)