More than a decade ago, spin [1] and charge stripe order [1,2] was discovered in La$_{2-x-y}$Nd$_y$Sr$_x$CuO$_4$ - a low-$T_c$ member of the cuprate family of superconductors. It was conjectured [1] and subsequently verified when stripe order was also observed in another low-$T_c$ cuprate, La$_{2-x}$Ba$_x$CuO$_4$ [3], that stripe order is stabilised once these materials undergo a structural transition from the low-temperature orthorhombic (LTO) common to La$_{2-x}$Sr$_x$CuO$_4$ to a low-temperature tetragonal (LTT) phase. If stripe order and superconductivity compete, these results naturally explain the deep narrow minima around $x \approx 1/8$ in the $T_c$ versus hole-content, $x$, curves in La$_{2-x-y}$Nd$_y$Sr$_x$CuO$_4$ and La$_{2-x}$Ba$_x$CuO$_4$. By contrast, in orthorhombic La$_{2-x}$Sr$_x$CuO$_4$ the minimum in $T_c$ is much more shallow near $x \approx 1/8$, amounting essentially to a few-degree Kelvin decrease as opposed to the ~25K dip in La$_{2-x}$Ba$_x$CuO$_4$. On the other hand, experimental probes sensitive to local magnetic order, such as NMR and muon spin rotation, have revealed a sharp maximum around $x \approx 1/8$ in the spin freezing temperature below which static magnetic order develops [4]. This and other suggestive pieces of evidence for stripe order in La$_{2-x}$Sr$_x$CuO$_4$ lead us to propose a search for signatures of charge stripe ordering near $x=1/8$. Our BW5 experiments, conducted in 2011, were encouraging and suggest that charge order does occur in La$_{2-x}$Sr$_x$CuO$_4$ when orthorhombic twinning is pronounced – a result broadly in agreement with recent resonant scattering evidence for charge order at the surface of La$_{2-x}$Sr$_x$CuO$_4$, $x=0.12$ [5]. In the initial part of our February-March 2012 experiment, we tracked the charge order signal in La$_{2-x}$Sr$_x$CuO$_4$ up to 17T. We used a high-field magnet designed for neutron and x-ray beamline use, operated by Birmingham University. The results indicate that as superconductivity is suppressed by the application of a magnetic field, charge ordering is favoured.

Subsequently, to test whether charge ordering occurs more generally in copper oxide superconductors, beyond the La124 family, we proceeded to look for charge ordering evidence in high-quality, oxygen ordered YBa$_2$Cu$_3$O$_{6+x}$. Materials belonging to the Y123 family of copper oxides are generally regarded as much less affected by quenched disorder than La124 – in particular when the excess oxygen forms ordered superstructures. Such Y123 samples form clean
venues in which to look for evidence of charge order. Before our experiments [6] and resonant elastic x-ray scattering work by Ghiringhelli and coworkers [7], indirect evidence for charge ordering in Y123 had come from the observation of high-field quantum oscillations indicating Fermi surface reconstruction (See e.g. Ref [8]) and from NMR [9]. The latter paper proposed that charge ordering in Y123 would be characterized by the same propagation vector as observed in La124, i.e. $Q_{ch} \approx (1/4 \ 0 \ 0)$. Our BW5 experiments in March 2012, showed that indeed charge ordering does occur in ortho-VIII YBa$_2$Cu$_3$O$_{6.67}$, but $Q_{ch1} \approx (0.3045 \ 0 \ 0.5)$ and $Q_{ch2} \approx (0.3146 \ 0 \ 0.5)$. The charge order correlations are long-ranged in the CuO$_2$ planes, $\xi_{ab} \approx 100$ Å, but short range, $\xi_c \approx 7$ Å, along the c-axis. The temperature dependence of the signal reveals a competition between charge order and superconductivity: Upon cooling below the superconducting transition temperature, $T_c=67$K, of our sample, the charge order signal drops [6]. The same result had been published by Ghiringhelli and coworkers [7], who, however, were unable to precisely identify the charge ordering wavevector owing to their limited reciprocal space coverage. Upon application of a magnetic field, we showed that the competition between superconductivity and charge order can be tuned in favour of the latter: The charge ordering Bragg peaks intensity increases approximately linearly with field and is more than doubled at our maximum field of 17T [6], as shown in the Figure below.

![Figure 1: Temperature dependence of the peak intensity of the $Q=(1.695 \ 0 \ 0.5)$ Bragg satellite peak in ortho-VIII ordered YBa$_2$Cu$_3$O$_{6.67}$ ($T_c=67$K). In zero external field, the charge density wave (CDW) ordering signal emerges gradually below $T_{CDW} \approx 135$K, i.e. in the normal state. The CDW signal grows upon cooling until $T=T_c$, below which it drops due to competition with superconductivity. Upon application of a magnetic field, superconductivity is suppressed causing the quasi-two dimensional CDW signal (long-range ordered in the CuO$_2$ planes, short range ordered between) to increase significantly [6].](image)

References