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# MEASUREMENTS OF BEAM CORRELATIONS INDUCED VIA COUPLED RESONANCE CROSSING IN THE CERN PSB

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*Abstract*

Beam profile measurements in the LHC and its injector complex show heavy tails in both transverse planes. From standard profile measurements, it is not possible to determine if the underlying phase space distribution is statistically independent. A measurement campaign in the CERN PSB was carried out to introduce cross-plane dependence in bunched beams in controlled conditions, in view of characterizing the LHC operational beam distributions. The results of the measurement campaign demonstrate how heavy tails can be created via coupled resonance excitation of the lattice in the presence of space charge, in accordance with predictions from the fixed line theory. The coupled resonance introduces dependence between the different planes, which persists after the resonance excitation is removed.

## INTRODUCTION

In high energy colliders, an in depth characterisation of the beam distribution is paramount to anticipate the luminosity performance and how the beam will behave under loss processes, particularly for high brightness beams. Beam profile measurements are the projection of the 6D phase space distribution onto a single plane (one of the horizontal, vertical and longitudinal planes). Inversions of these projections do not yield unique solutions for the full beam distribution, and both factorizable and non-factorizable distributions can be matched and fit the measured projections in uncoupled machines [1]. Non-factorizable distributions contain correlations between planes, that is selecting the amplitude of a particle in one plane will condition the amplitude distribution in another plane. This impacts in a macroscopic way the evolution of the particle distributions, for example, losing a particle in one plane affects the distribution of the particle (normalised) profile in the other. This can be observed experimentally through scraping of the beam tail, and measurement of the beam profile in the other planes.

Crossing of coupled x-y resonances is one mechanism that can introduce the aforementioned correlations. Due to the synchrotron motion in bunched beams, particles change their position within the longitudinal profile. The space charge tune spread depends on the local line charge density, and thus it is changing as the particles move towards the centre of the bucket. Particles which were initially not resonant become resonant as their tune approaches the resonant condition. In the case of 2D coupled resonances, they are trapped or scattered by ‘fixed lines’ [2], which have been the subject of recent theoretical and experimental investigations [3–6]. The fixed lines are structures visible in the $x$-$y$ Poincaré sections, resembling Lissajous figures. These curves are correlated in the $x$-$y$ planes, which explains how correlation is built into the distribution when particles are trapped or scattered to higher amplitudes by these structures. When the particles no longer meet the resonant condition, the correlations persist as the Courant-Snyder amplitudes in $x - p_x$, $y - p_y$ of a given particle are preserved [7].

The results presented in this contribution demonstrate experimentally how periodic crossing of 1D and 2D third-order resonances in the presence of space charge, create lasting phase space correlations (in two planes for 1D resonances, and three planes for 2D coupled resonances). The results show the effect of periodic resonance crossing on correlations on the longitudinal plane, previously not presented in [8].

## EXPERIMENTAL SETUP

The measurement campaign was performed at the CERN Proton Synchrotron Booster (PSB), which is a machine with four superposed rings with a common magnetic yoke, and all experiments were conducted in Ring 1, the bottom ring. The driving terms of the relevant lattice resonances for the chosen working points were corrected for, as detailed in [9]. This enabled controlled excitation of the selected resonance. Two experimental configurations are presented: the working point $(Q_x, Q_y) = (4.11, 4.36)$ near the skew third order resonance $3Q_y = 13$, and $(Q_x, Q_y) = (4.18, 4.44)$ near the normal coupled third order resonance $Q_x + 2Q_y = 13$. The tune spreads due to space charge are around $\Delta Q_x = -0.11$, $\Delta Q_y = -0.14$.

Figure 1 illustrates the experimental configuration of the cycle. The measurements were performed at the 160 MeV injection plateau, during which a single bunch of 40e10 pro-

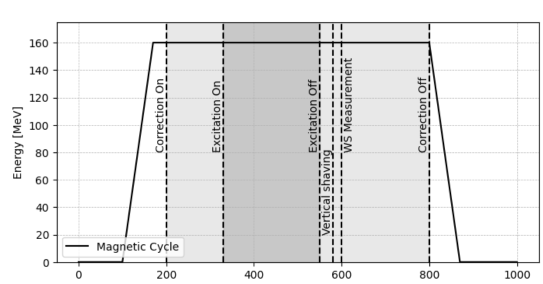


Figure 1: The experimental setup along the 160 MeV injection plateau in the PSB.

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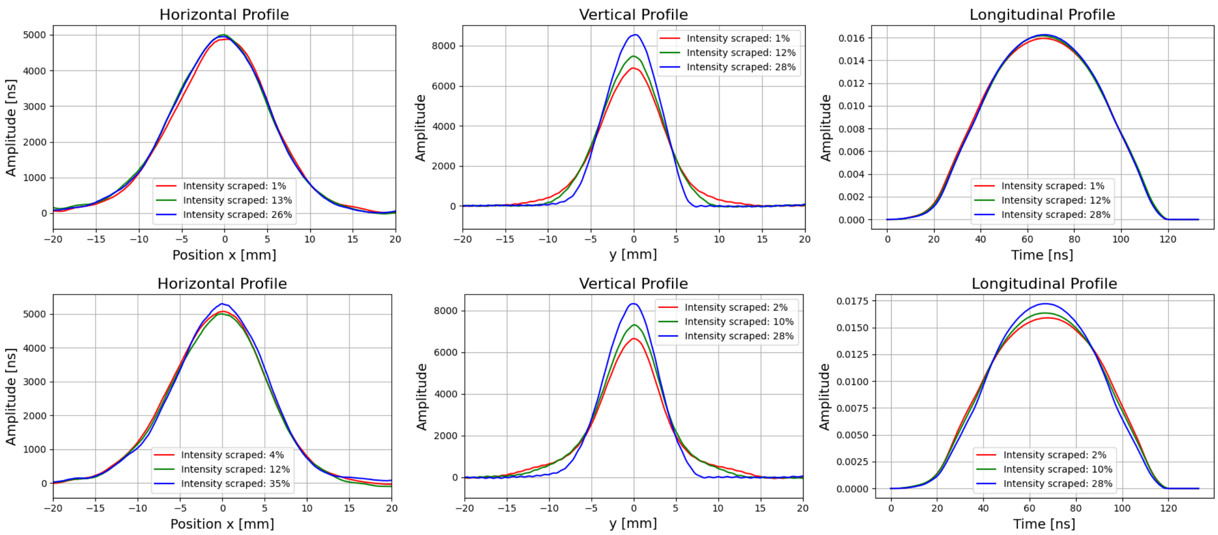


Figure 2: Beam profile measurements near the $3Q_y = 13$ vertical resonance. The measurements are after vertical scraping has removed different intensities as per the colour scale, without (top) and with (bottom) the resonance excited by a strongly powered skew sextupole for some period of the cycle.

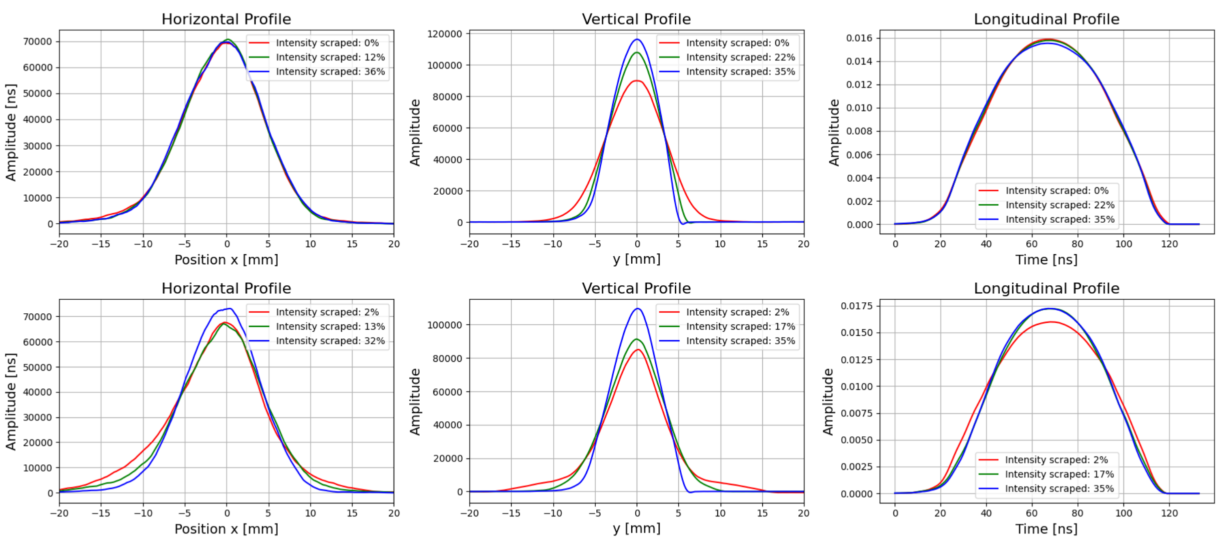


Figure 3: Beam profile measurements near the $Q_x + 2Q_y = 13$ coupled resonance. The measurements are after vertical scraping has removed different intensities as per the colour scale, without (top) and with (bottom) the resonance excited by a strongly powered normal sextupole for some period of the cycle.

tons was stored. The lattice resonance compensation was maintained during the whole cycle. Measurements were performed with either no resonance excitation, or with a resonance excitation for a period of 220 ms using a skew or normal sextupole, depending on the selected resonance. Following a period of 30 ms (~$30{\times}10^3$ turns), corresponding to around 20 synchrotron periods after the excitation was removed, high amplitude particles of the vertical profile were scraped away via a controlled vertical closed orbit bump moving the beam onto a dedicated aperture restriction. Profile measurements in the horizontal and vertical plane were taken with the wire scanners after the scraping process, along with tomoscope measurements [10] for the longitudinal plane. The sextupole strength and vertical bump were varied to test how the correlations change as function of the particle amplitude for different resonance excitations.

## EXPERIMENTAL RESULTS

Figure 2 displays the vertical, horizontal and longitudinal profiles for different scraped intensities (done with the vertical scraping bump), with and without the resonance excitation. When the $3Q_y = 13$ resonance is not excited, the profiles (normalised to intensity) remain constant in the non-scraping planes (apart from shot to shot variation). When the $3Q_y$ resonance is excited, large tails can be observed in the vertical plane, which are clearly removed by the scraping.

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Furthermore, the vertical scraping also changes the longitudinal profile resulting in reduced bunch length, as particles with large vertical amplitude also have high longitudinal amplitude, which can be explained by the periodic resonance crossing induced by space charge. The horizontal profile is not changing, as the 1D resonance crossing moves particles to higher amplitudes in the vertical plane only for $3Q_y = 13$.

Figure 3 shows the beam profiles in all three planes when measured after the vertical scraping for the resonance $Q_x + 2Q_y = 13$ for different scraped intensities, with and without the excitation during the cycle. As the beam is scraped vertically, for the case with no excitation, the normalised longitudinal and horizontal profile do not change beyond shot to shot variation. For the case with the resonance excited, the non-scraped profile has larger tails in both H and V. As the vertical tails are removed by the scraper, both the horizontal as well as the longitudinal profile change shape. This suggests that particles which have been affected by the resonance have moved to high amplitudes in the vertical and horizontal planes, and a section of the distribution with large longitudinal amplitude is affected by the resonance. This is again compatible with space charge induced resonance crossing.

To see the effect of different levels of resonance excitation, the transverse profiles are fitted with a q-Gaussian distribution [11, 13], where the $q$-parameter shows how heavy ($q > 1$) or light tailed ($q < 1$) the distribution is compared to a normal Gaussian ($q = 1$). The bunch length is determined from the tomoscope data and represents the RMS length of the profile. The error given is for the standard deviation of the RMS during the measurement of the tomoscope (100 profiles for one measurement). Figure 4 shows the bunch lengths and the $q$-parameters of the transverse profiles ($q_H$ for the horizontal fit and $q_V$ for the vertical fit) for different sextupole strengths exciting the $Q_x + 2Q_y = 13$ resonance, with the error from the covariance matrix of the fitting.

In the case of 0 amps, it can be seen there is almost no dependence of $q_H$ and bunch length on $q_V$ (as the beam is scraped in the vertical plane), meaning little or no other coupling or resonant effects are present. At 20 amps, there are tails created in H and V, and they are correlated up to a scraping of 15%, along with the longitudinal bunch length. At 40 amps, the tails generated by the periodic resonance crossing are even thicker and the three parameters remain correlated until a vertical scraping of 22%. Increasing the resonance excitation increases the correlations in the 6D phase space distribution.

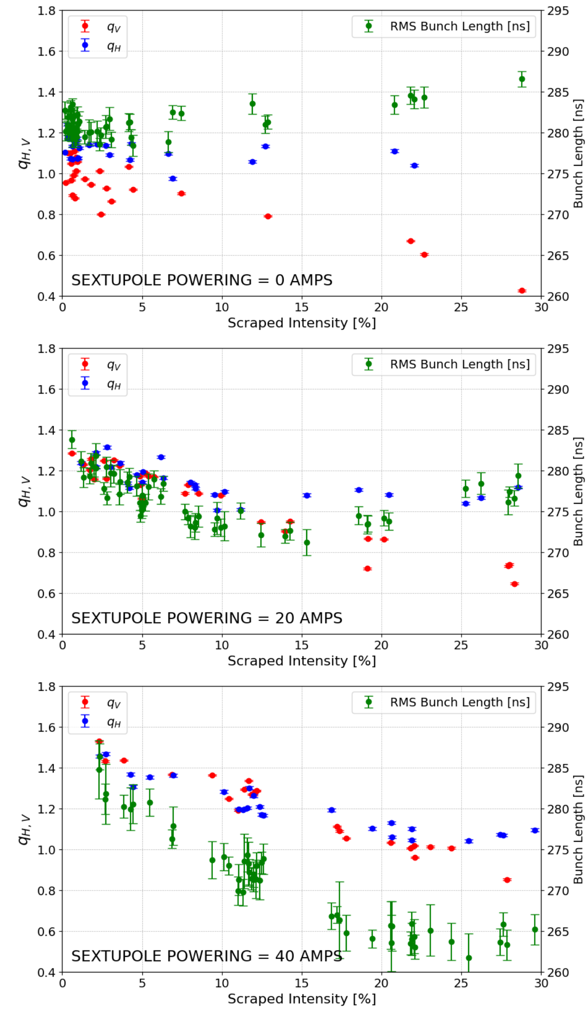


Figure 4: Bunch length, $q_v$ and $q_h$ plotted as a function of the scraped intensity for the $Q_x + 2Q_y = 13$ configuration. The three plots are for increasing sextupole powering, (0, 20 and 40 amps from top to bottom).

## CONCLUSION

We have demonstrated experimentally that a beam subject to a resonance with controlled excitation forms tails in the transverse plane(s), which leads to correlations in the phase space distributions. Consistent with space charge induced periodic resonance crossing, these correlations are between the vertical and longitudinal plane for a purely vertical resonances, and between both transverse planes and the longitudinal plane for a coupled resonance.

These correlations are measured after the resonance excitation is removed, illustrating how correlated distributions can be obtained and matched in uncoupled machines. Further experiments are ongoing to determine how properties of phase space distributions are maintained along the CERN injector chain. Simulations will form part of future work to investigate how emittance, space charge and distance to the resonance in tune space affect these correlations.

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