# On-line Phase Space Measurement with Kicker Excitation

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**Abstract.** A new method for on-line phase space measurements with kicker excitation at COSY was developed. The position data were measured using the analog output of two beam position monitors (BPMs) and directly monitored on a digital storage oscilloscope with an external clock (bunch-synchronous sampling). Nonlinear behavior of the proton beam was visible as well as were resonance islands. Typical measurements are presented.

## INTRODUCTION

COSY is a cooler synchrotron and storage ring, delivering protons (unpolarized or polarized) with momenta between 300 MeV/c and 3300 GeV/c for experiments in medium-energy physics. It contains two cooling systems to shrink the beam phase space. An electron-cooling system reaches up to a momentum of 600 MeV/c and is complemented by a stochastic cooling system that covers the upper range from 1500 to 3300 MeV/c. Beam extraction is accomplished by the conventional resonant extraction mechanism as well as with the stochastic extraction method. Proton beams are routinely delivered to three internal and three external experimental areas (1). In this paper, special emphasis is given to the measuring technique of the transverse phase space. The knowledge of the phase space near the electrostatic septum is essential for optimization of the resonant extraction process and very useful for beam dynamics experiments.

## EXPERIMENTAL SETUP

The experimental procedure starts with exciting the beam particles to collective transverse (in our case only horizontal) oscillations with betatron frequency by a fast diagnostic kicker magnet in the COSY ring. The beam bunch is short-time deflected (0.75 µs – 2 µs width, rise and fall time < 1µs) and the resulting bunch oscillations are measured using the beam position monitors (BPMs). The kicker excitation is synchronized with the COSY rf signal and can be adjusted in time by programmable delay, so that a single deflection of the total bunch can be performed (bunch synchronous excitation). The amplified and filtered sum and difference signals from the BPM electrodes are digitized by flash ADCs (20 MHz clock rate), stored in FIFO memories (4K or 64K width), and transferred to files. Depending on the FIFO width, data of about 200 or 3200 successive turns can be stored. Up to now, the phase space was calculated from the raw data of two BPMs and MAD calculations for TWISS parameters ($\alpha,\beta,\gamma$) (2). Now a new method has been developed. The position data are measured using the analog output of two BPMs and directly monitored on a digital storage oscilloscope. The sum signal of a BPM is used to detect a passing bunch. The signal is differentiated and fed into a PLL-circuit. The differentiated sum signal has a zero crossing at each bunch peak, nearly independent of the bunch-shape and the bunch frequency. The phase loop tracks the zero crossing point and generates a clean, jitter-free clock pulse in phase with the bunch peak (Fig. 1). The output signal controls the sampling of the oscilloscope input stages (external sampling clock). Two BPM difference signals are displayed on line in the *xy*-display mode. The time of flight between the two BPMs is compensated by an electrical delay. The display represents the position of one BPM versus the other (except the calibration). To get the phase space diagram (angle $x_1'$ versus position $x_1$), the transfer matrix between the two BPMs must be known. Another representation uses the normalized momentum $p_1 = \alpha \cdot x_1 + \beta \cdot x_1'$ versus position $x_1$ (canonical coordinates $x_1, p_1$). If the phase advance between the two BPMs is equal to $\pi/2$, the following expression for the normalized momentum $p_1$ is found:

$$p_1 = \sqrt{\frac{\beta_1}{\beta_2}} \cdot x_2; \tag{1}$$

that means monitoring $x_2$ versus $x_1$ is similar to $p_1$ versus $x_1$ except the factor $(\beta_1/\beta_2)^{1/2}$.

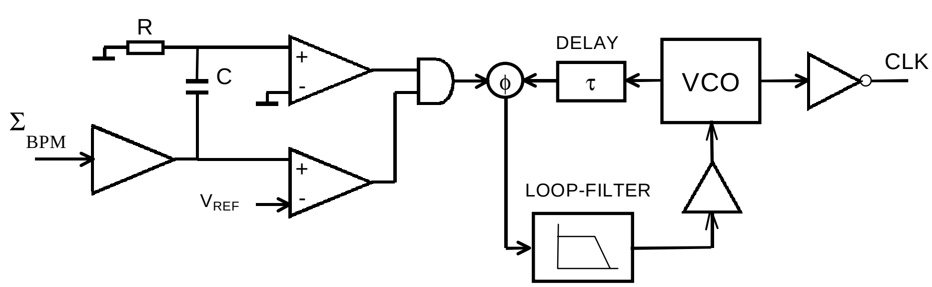


**FIGURE 1.** Bunch-synchronous tracking generator.

## EXPERIMENTAL RESULTS

A problem for such measurements is the "damping" of the oscillations due to the finite betatron frequency spread of the particles. Typically, about 100 oscillations are seen in our case. To overcome this problem, the measurements were performed with a cooled beam. Figure 2 shows the on-line horizontal "phase space" plot (difference signal $BPM_{x24}$ versus difference signal $BPM_{x22}$) near a third-order resonance for four different kick strengths (deflection angles) with an electron-cooled beam (approximately $5 \cdot 10^9$ circulating stored protons, momentum 1.675 GeV/c). Under these conditions, more than 40000 oscillations could be observed. The momentum deviation $\Delta p/p$ is about $2 \cdot 10^{-3}$ before and $1 \cdot 10^{-4}$ after cooling the beam. A sextupole (nonlinear) magnetic field is used to excite the third integer resonance (in this case the horizontal tune amounts $Q_x = 11/3$).

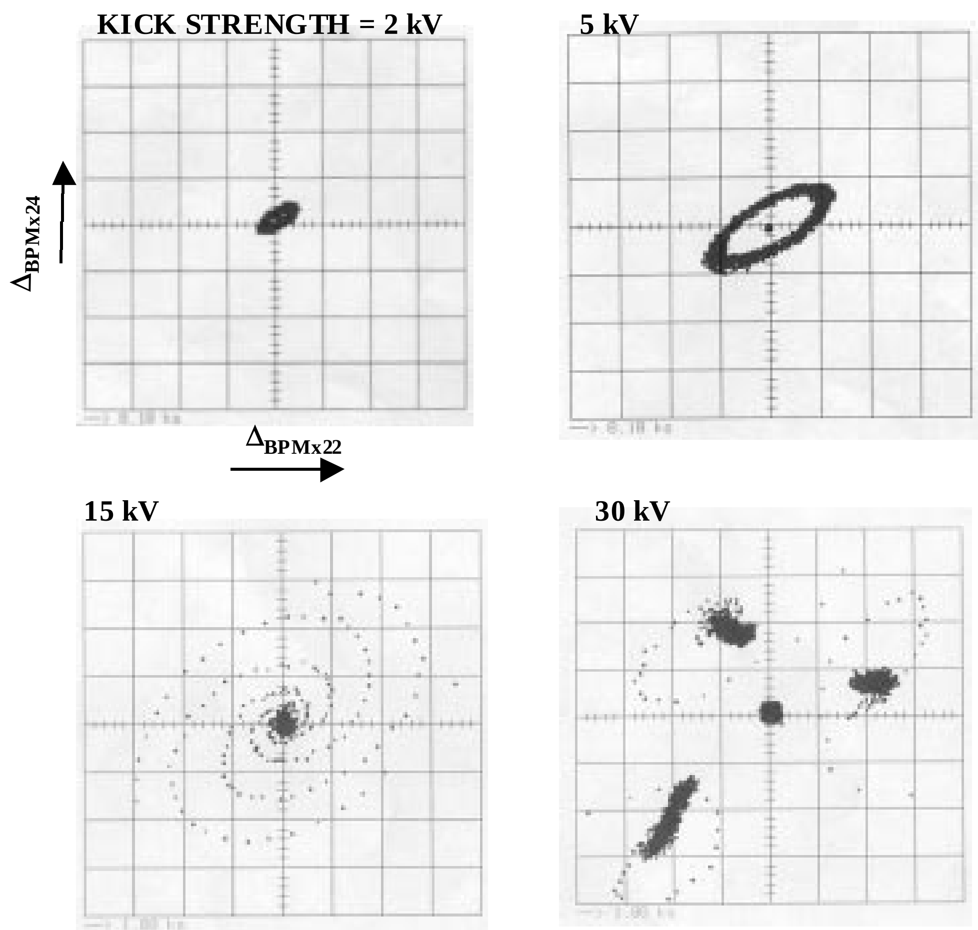


**FIGURE 2.** Horizontal "phase space" plots of an electron-cooled beam at four different kick strengths in kV (deflection angles) displayed on line with a digital storage oscilloscope in *xy*-display mode. Vertical direction: analog difference signal of $BPM_{x24}$, horizontal direction: analog difference signal of $BPM_{x22}$.

The effect of the nonlinearity makes the tune increase with increasing kick amplitude, so there is one amplitude for which the tune is exactly 11/3. Furthermore, there is a frequency entrainment effect causing all nearby amplitudes to lock onto exactly the same tune. This accounts for the existence of so-called resonance islands (3). When the beam is kicked with a small amplitude, the particles are not kicked upon the resonance. At a certain amplitude, the "lock-on" is visible and islands are formed (see Fig. 2). During the first 100 turns, the motion is damped before the particles are trapped in the island. The particles jump to another island at each turn and return to the starting island after three revolutions. The bunch within the island performs a circular motion around the center of the island, the so-called stable fixed point. After about 37 turns, the bunch returns to its original position in the island.

## CONCLUSIONS

The studies of beam centroid motion after collectively perturbing the beam by a fast kicker yield important information about the lattice. This procedure is also useful in nonlinear beam dynamics studies. Due to the non-negligible beam size, the interpretation of the experimental results is difficult, especially if the beam center is displaced close to the separatrix. Some of the particles are stable here, some are instable. The degree to which the beam centroid motion accurately represents the motion of a single particle depends on the emittance of the beam; the smaller the emittance of the beam, the more accurate is its representation of single particle motion. Further limitations are the decoherence of the betatron motion and crossing of nonlinear resonances.

The shown method is extremely useful in determining the transverse phase space on line without analyzing the digitized FIFO memory of the beam position monitors.

## REFERENCES


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