Beam Position and Profile Measurements at BESSY

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We describe techniques used at the synchrotron light source BESSY to determine position and profile of a low emittance electron beam. Measurements are presented which yield important information on the process of beam blow-up due to ion accumulation at low current. At sufficiently high currents the ions are cleared from the beam.

Beam Position Measurements

The transverse beam position is measured by electrostatic pick-up monitors (PIMS). There are 12 measuring stations distributed approximately equidistantly around the storage ring BESSY (1). Each station consists of 4 pick-up plates of 15 mm diameter allowing for both horizontal and vertical position measurement. The signals are transferred to the control room without amplification via a two stage multiplexer system and coaxial cables of about 50 m total length.

We measure the amplitude of typically 200 mV of the 500 MHz component by a commercial vector analyzer. The beam positions are determined from the difference and sum of the voltage of two opposite pick-up plates. Corrections are applied for different cable dampings (~ 10 dB). As usual we assume a linear voltage dependance of the beam displacement, using experimentally determined calibration factors.

The system is checked by consecutive multiplexer switching and repeated voltage measurements for every PIM. This procedure leads to measurement times of up to 10s per PIM. Successive measurements reproduce the spatial position to about 10 µm. Spatial errors introduced by the decreasing beam current are less than 50 µm for beam lifetimes greater than 30 min.

The position of the PIM stations with respect to the magnetic axis of the quadrupoles is obtained from a survey of the storage ring. We estimate the absolute error of the beam position measurement to be less than 0.1 mm.

For the measurement of small beam movements, e.g. determination of the tune of the machine, however, optical systems imaging the electron beam using the visible part of the synchrotron radiation spectrum emitted in bending magnets are superior to the conventional pick-up monitors described above. A photomultiplier is located behind a pinhole placed in the wing of the intensity distribution of the image of the electron beam. A change of beam position causes a signal change proportional to $1/\sigma$. At BESSY the rms with σ of these distributions is between 50 µm and 200 µm. With a pick-up plate a signal change would only be proportional to 1/R where R is the distance between electron beam and pick-up plate. R is of the order of 30 mm. Therefore, pick-ups are used only for routine tune measurements.

Results

For studies of current dependent tuneshifts the optical detector was used. Figure 1 shows the result for the standard operation of the storage ring with about 70 out of 104 buckets filled with electrons leaving a gap for ion clearing (2). The beam has been excited by a short pulse and the motion of the beam was recorded and averaged with a fast ADC. The beam motion should be smaller than one µm in order not to disturb the highly nonlinear interaction between the electron beam and the collected ions. The decay of the coherent motion is Fourier-transformed and the peak and the width of the frequency component are displayed in Figure 1. Our results indicate ion trapping accompanied by tuneshift and tunespread (3) for electron currents between 0.25 mA and about 60 mA. For very low beam currents the kinetic energy of the ions exceeds the potential of the electrons. For higher currents the motion of the ions in the potential of the beam becomes unstable. Thus, the electron beam clears itself from ions. According to the theoretical expectations (2) this mechanism only works with a partial filling of the storage ring.

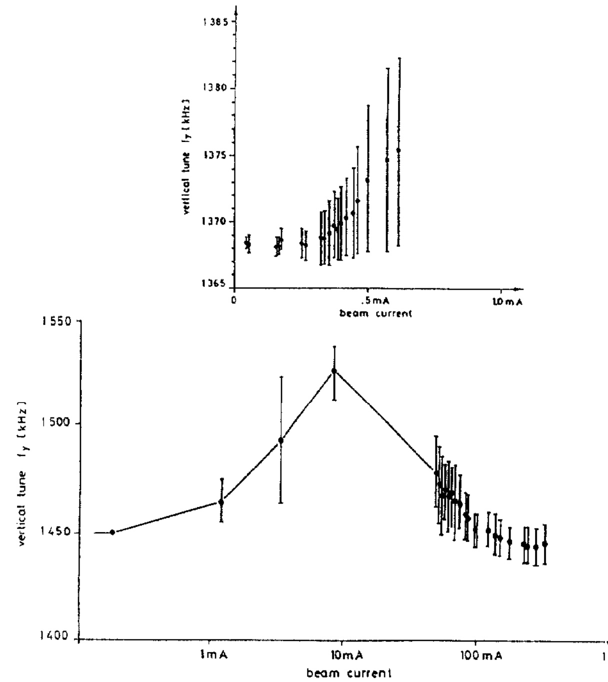

Fig. 1: Current dependent vertical tune shift and tune spread due to ion trapping.

Beam Profile Measurements

The profile of the stored electron beam is measured with optical systems. At BESSY currently three of these optical systems are in use (4). Using a metal mirror the synchrotron radiation is reflected out of the storage ring plane through an optically flat vacuum window into an imaging system. The imaging element is either a mirror or a lens with a color glass filter. We use various techniques to scan the image of the beam (4). The data presented here have been taken with two different systems.

The first one is similar to the set up described by Ebeling (5). The image is scanned rapidly with a random access camera (image dissector) and the signal is processed electronically. The output at a rate of 1000 Hz are on-line values for the position and the profiles of the image of the electron beam. These values are available as digital or analog data.

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The second system works in the following way: A rotating mirror moves the image over a slit and a time varying signal is created in a photomultiplier behind the slit. The axis of rotation and the direction of the incoming light are identical, while the rotating mirror is at 45 degrees with respect to this axis. Instead of two detectors we use one additional fixed mirror to pass the image rotated by 90 degrees over the same slit.

In this way vertical and horizontal intensity distributions are scanned with only one detector. The full width at half maximum (FWHM) of these distributions is determined electronically and analog signals proportional to the horizontal and vertical FWHM of the electron beam are available.

The resolution of both optical systems is limited, mainly by diffraction, to about 100 µm FWHM (4). The random access camera optical system is installed at a position in the storage ring where the horizontal dispersion function is 30 cm, whereas the rotating mirror is located at a position of vanishingly small dispersions. For visual inspection the intensity distributions of both systems are displayed permanently on oscilloscopes.

Results

Figure 2 shows photographs of the intensity distribution produced by the random access camera. They have been taken at currents of 340 mA (top) and 250 mA (bottom) using a partial filling mode and the 62.5 MHz rf-system (6). 8 or 9 out of 13 buckets are filled. The vertical profile is smaller than the horizontal one. At the higher current the beam can become longitudinally unstable. The beam is then horizontally broadened due to the dispersion (top).

Figure 3 shows the horizontal width of the beam. These measurements have been performed with the random access camera and a partial filling, using the 500 MHz and 62.5 MHz cavity system. At positions with dispersion the heating of the energy distribution causes a significant current dependence of the horizontal beam size. We estimate an energy spread of 4.E-3 from the measured beam size at 400 mA. This is nearly one order of magnitude larger than the natural energy spread. A longitudinal impedance of the BESSY storage ring of 2.5 ± 1 Ohm has been determined from the current dependence of the width of the beam in single bunch operation using the low frequency cavity system. The rotating mirror optical system showed no current dependent effects in the horizontal profile due to the vanishing dispersion.

Both optical systems are designed to evaluate the profiles as fast as possible. The tune dependance of the beam size can be measured easily. We scanned the tune diagram along the dotted lines in figure 4 by varying the settings of two quadrupole families and looked for beam blow-up caused by the crossing of resonances. Resonances up to third order are indicated in the figure.

In figure 5 we present our measurements along line no. 1 in figure 4. A single bunch has been used to avoid longitudinal instabilities. Sextupoles have been adjusted to compensate the chromaticities at least partially. These measurements were taken with the rotating mirror before the vertical closed orbit has been corrected. Therefore the coupling was strong and the vertical FWHM was not smaller than 0.3 mm.

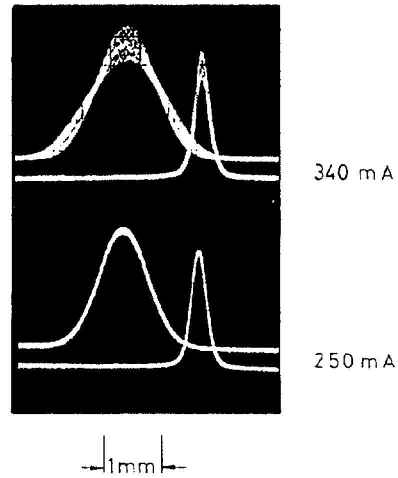

Fig. 2: Horizontal (left) and vertical (right) intensity distribution taken with the random access camera. The horizontal beam size is enlarged due to a current dependent longitudinal instability (top).

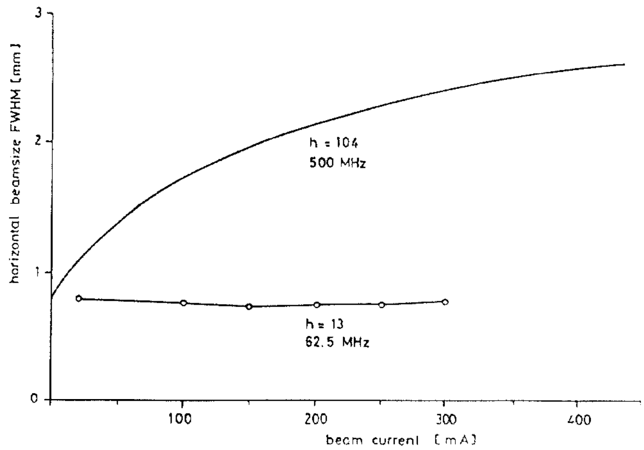

Fig. 3: Horizontal beam size as a function of beam current with short (h=104) and long bunches (h=13).

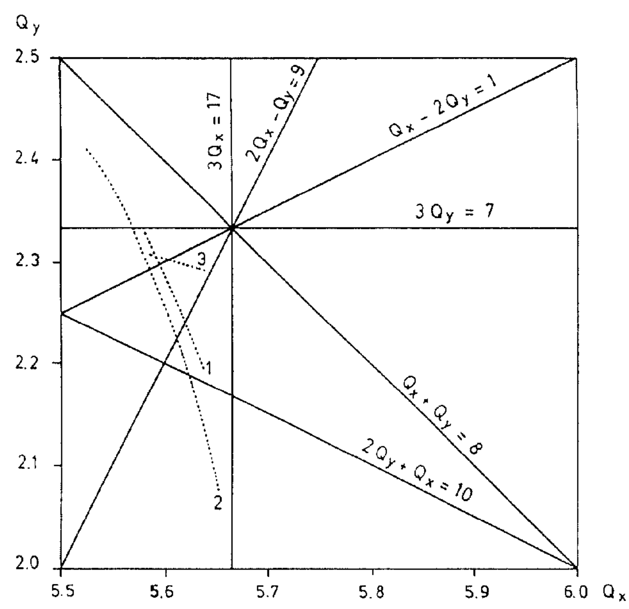

Fig. 4: Tune diagram showing resonances up to third order. Tune variations are indicated as dotted lines.

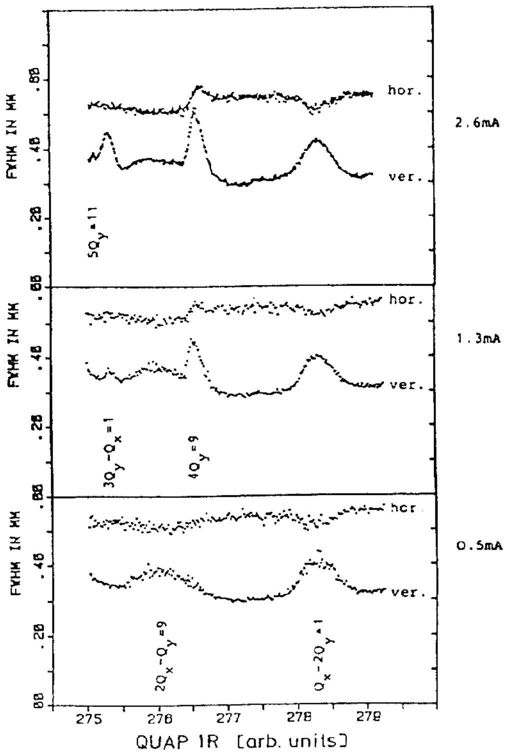

Fig. 5: Horizontal and vertical beam size of a single bunch as a function of tune at various currents. At low currents (buttom) only third order resonances occur. At high currents trapped ions drive higher order resonances (top).

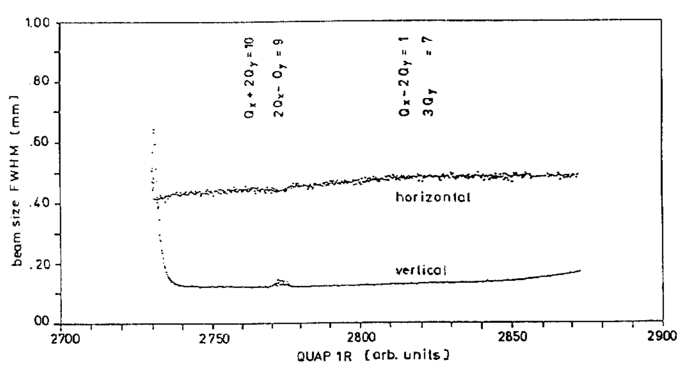

Fig. 6: Beam size as a function of tune. The vertical orbit was carefully corrected. Without sextupoles only minute non-linear effects appear.

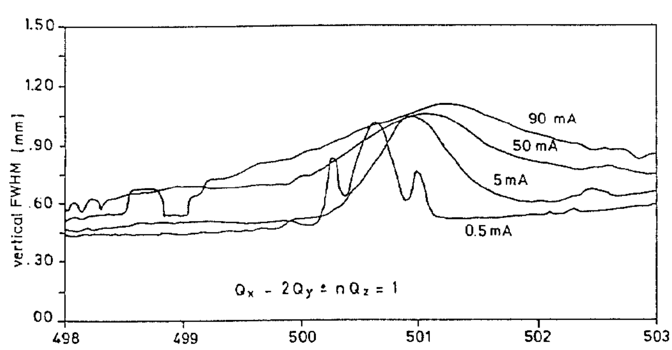

Fig. 7: Vertical beam profile around the $Q_x - 2Q_y \pm n\,Q_z = 1$ resonance as a function of the beam current.

At low current only the third order resonances $2Q_x - Q_y = 9$ and $Q_x - 2Q_y = 1$ occur due to skew and regular sextupole field components. These difference resonances cause an increase of the vertical and a reduction of the horizontal profile. The coupling does not depend on the beam current. It is created by static magnetic fields in the storage ring. At beam currents above the ion trapping threshold higher order resonances appear. Their current dependent strength indicates that they are caused by the non-linear fields created by the accumulated ions.

Figure 6 shows the result of a similar experiment at low current. The tune was varied according to line 2 in figure 4. The sextupoles have been switched off and the vertical orbit was carefully adjusted to reduce the coupling to a very low value. In this picture only the $2Q_x - Q_y = 9$ resonance shows up. However, the other resonance driven by skew sextupoles namely $3Q_y = 7$ is observed as a reduction in lifetime.

Figure 7 shows the current dependence of the vertical profile around the resonance $Q_x - 2Q_y \pm n\ Q_z = 1$. The storage ring was chromaticity compensated and only partially filled. The tune has been varied along line 3 in figure 4. At very low beam currents (0.5 mA) the synchro-betatron resonances are clearly resolved. At higher currents this resonance is shifted and broadened due to the collection of ions. Notice the stepwise change of the vertical beam size at the left hand side of that figure! These steps are more dependent on current and time, than on tune. This indicates that at higher currents and away from a resonance, which would lead to beam blow-up, the beam size can become as small as at low currents.

At BESSY the following steps have been taken to avoid the collection of ions (1):

1. The vertical orbit was carefully adjusted to reach a very small vertical beam size. Coupling of about 1 % was achieved.
2. The tune was chosen to avoid resonances which would cause a beam blow-up. This condition must be fulfilled for currents up to the upper ion trapping condition (3).
3. We use a partial filling of the storage ring and leave a gap of empty buckets. This drastically improves ion clearing (2).

With these precautions we observe thresholds for ion clearing in fair agreement with theory (2,3).

Acknowledgement

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