ACCELERATOR PHYSICS EXPERIMENTS WITH BEAM LOSS MONITORS AT BESSY

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Abstract

The extended use of beam loss monitoring has led to a better understanding of the linear and non-linear physics involved in the single and multiple particle dynamics at BESSY. This knowledge has been used for improving the performance of the light source in terms of lifetime, beam stability, and stability of the energy.

The key to these experiments are loss monitors placed at strategic locations of the ring with high sensitivity to Touschek or Coulomb scattered particles.

Coulomb-scattering depends strongly on the transverse dynamics which is determined by the magnetic guiding fields. Losses occur primarily at the vertical aperture restrictions imposed by the flat insertion device vacuum chambers. Tune scan measurements clearly show resonances produced by the lattice magnets and by some of the insertion devices.

Touschek scattering depends on the 3-dimensional electron density and the spins of the colliding particles. In transfer function type experiments these dependencies have been used to observe the effect of resonant transverse and longitudinal beam excitations. Loss monitors allow to detect excited head-tail and higher longitudinal modes which are invisible in the center of mass motion. Another application is the detection of the resonant destruction of the spin polarization of the ensemble of electrons. This is used routinely in order to determine the beam energy with high accuracy.

1 INTRODUCTION

The lifetime of the stored beam current, or its inverse, the decay rate of the intensity, is a very convenient measure of global particle losses. However, a fast and accurate determination of this quantity is difficult. The limited resolution of current monitors require long time intervals, Δt, in order to detect significant changes of the intensity, ΔI, especially if the lifetime, τ, is large since $\Delta I/I=-\Delta t/\tau$.

The alternative is the direct local detection of lost particles. When high energy particles are hitting the vacuum chamber, they produce a shower of many particles with low energy like photons, electrons, and positrons. These fragments are emitted into a small cone in the forward direction and they are easy to observe with different types of detectors[1]. With beam loss monitors (BLM) placed close to the vacuum chamber each lost electron at that location can be detected. Particles hit the chamber at specific locations depending on the loss mechanisms involved. With a system of strategically distributed loss monitors the detection is sensitive to the mechanisms causing the loss.

The high speed of the measurements and the information on the loss mechanisms have been exploited by correlating beam losses with parameters like external transverse and longitudinal excitations, the working point, different settings of machine parameters, the beam current, and further more.

2 PARTICLE LOSS MECHANISMS

Experiments have been performed at the second generation light source BESSY I, an 800 MeV electron storage ring, and the third generation source BESSY II operating at energies between 900 MeV and 1.9 GeV[2]. Dominating, unavoidable particle losses in this energy range stem from the electron-electron interactions within one bunch, the so called Touschek effect, and interactions of electrons with residual gas molecules, like elastic and inelastic Coulomb scattering[3]. Particle losses can occur just downstream the collision point at the next transverse or longitudinal aperture restriction or at any other location if particles are scattered close to, but not exceeding the aperture limits. This introduces a background of losses which can not clearly be attributed to a specific loss mechanism.

2.1 Detection of Touschek Scattered Particles

Good locations for the detection of Touschek scattered particles are in the achromatic sections with the highest value of the dispersion function just behind straight sections where a high particle density is reached. Since the two colliding particles loose and gain an equal amount of momentum, they will hit the in- and outside wall of the vacuum chamber. In principle the selectivity of the detection to Touschek events can be improved by counting losses at these locations in coincidence.

2.2 Detection of Coulomb Scattered Particles

Losses from elastic Coulomb scattering occur at locations where the beta functions are large and where apertures are small. Aperture restrictions are introduced either intentionally, like in the case of small gap insertion device (ID) vacuum chambers, in-vacuum IDs, the septum magnet, and by mechanical scrapers or unintentionally by burned RF fingers and other obstructions.

If, in an inelastic Coulomb collision, the energy carried away by the emitted photon is too large, the particle gets lost behind the following bending magnet on the inside wall of the vacuum chamber.

3 DETECTION OF LOST PARTICLES

Over the years different detectors were tested at BESSY. The choice right now are plastic scintillation counters. A 3x3 cm^2 piece of the fast NE100 material is used. The light is coupled through a light pipe to the photo multiplier. Up to 42 of these beam loss monitors (BLM) can be distributed around the storage ring. The high voltage power supplies, the pulse shaping-electronics, and the discriminators are located on the gallery above the ring.

So far 12 detectors have been installed. 4 monitors are placed where a large contribution from particles lost due to the Touschek effect are expected. The remaining monitors are more sensitive to losses from elastic Coulomb scattering: 6 BLMs have been mounted at the end of the straight sections, on top of the small gap insertion device vacuum chambers and 2 BLMs are installed at the horizontal physical aperture limitation behind the injection septum magnet. With these 12 detectors a few percent of all lost electrons can be counted.

With this distribution a very good sensitivity for detecting Touschek losses is obtained, even without coincidence techniques. The selectivity for observing elastically Coulomb scattered particles is sufficient. Until now, no attempts were made to achieve selective detection of inelastic Coulomb scattered electrons.

4 EXPERIMENTS WITH LOSS MONITORS SENSITIVE TO COULOMB LOSSES

In the ideal case, the 3-dimensional distribution of particles in an electron storage ring is Gaussian. Coulomb scattering increases the population of the tails of the distribution. Any modification of the phase space will have an impact on the number of lost electrons. By observing losses related to elastically scattered particles as a function of the working point, the beam-beam interaction and the lattice related phase space were investigated[4]. At BESSY the non-linearity of the storage ring lattice as well as the one introduced by the IDs were analyzed with this technique.

4.1 Impact of Insertion Devices

The APPLE II type undulators UE56 show a dramatic impact on the lifetime of the stored beam at BESSY II[5]. In Fig. 1. two loss rates are shown as a function of the vertical tune for open and closed undulator gaps: vertical losses at one of the ID chambers and horizontal losses at the septum magnet. Loss rates and lifetime show the same tune dependence and exhibit very similar resonance-like features. Even though the upstream (red) and the downstream (green) part of the ID are nominally identical only the upstream part leads to severe losses at the nominal working point. This has to be attributed to statistical field errors of the ID and is not a systematic effect.

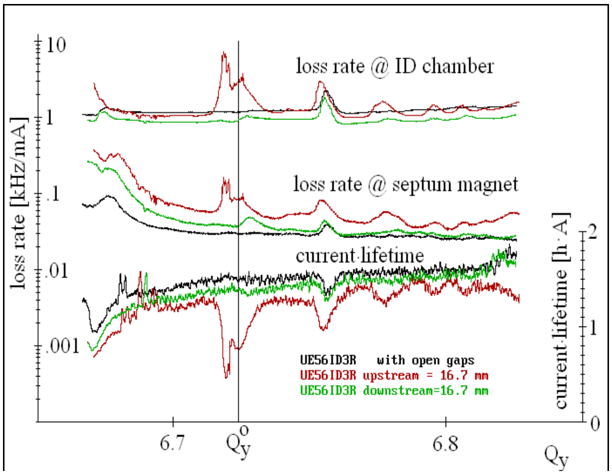

Fig. 1: Impact of two nominally identical IDs on beam dynamics. Lifetime and loss rates as a function of the vertical tune exhibit the same resonance-like features.

The high speed of loss rate detection even allows to perform tune scans as a function of other parameters. Tune scans as a function of the magnetic gap of the IDs show, how resonances get stronger and stronger the more the gap is closed. The UE56 is intended to produce light with variable polarization. By shifting the magnet poles longitudinally the electron beam wiggles either in the horizontal, the vertical plane, or, in between, it moves on a helical orbit. Tune scans as a function of the shift parameter show, that this parameter has no strong impact on the beam dynamics.

Two dimensional tune scans close to the nominal working point were performed in order to find out which resonance was responsible for the dramatic impact of the upstream part of the ID on the lifetime. Since there is a one to one relationship between the resonances and the multipole field component driving the resonance in lowest order this allows to pinpoint the harmful field components. The result is shown in Fig. 2. It is the $Q_x+3\cdot Q_y$-resonance which is driven by a skew octupole component. Many other resonances are excited by this ID. Better shimming should improve the situation considerably. For the time being, the working point was moved slightly away from the most harmful resonance.

4.2 Lattice Non-Linearity

Since the loss rates are high tune scans can be performed at lower beam currents where instabilities do not occur. Fig. 3 shows the losses at the vertical aperture limitation and Touschek losses as a function of the vertical tune with only 1 mA stored in a single bunch. All IDs are open and the resonances are excited by the lattice.

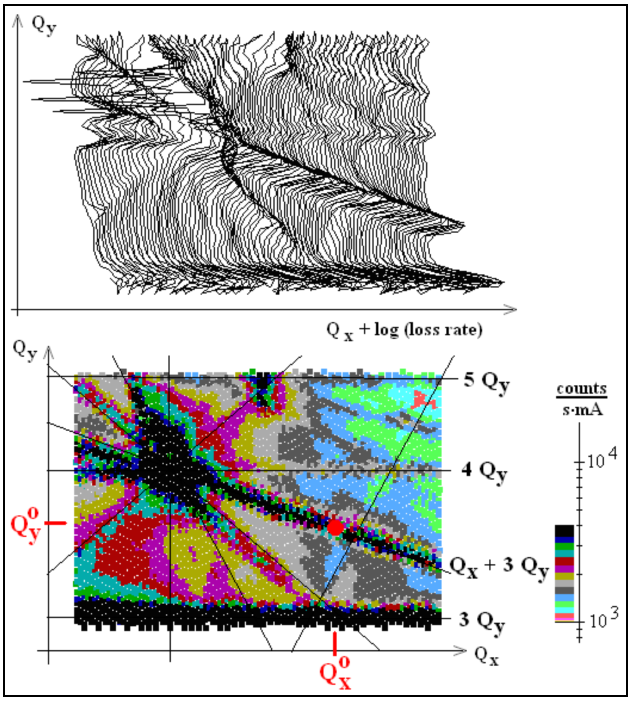

Fig. 2: 2-dimensional tune scan close to the nominal working point: Q_y=6.72 and Q_x=17.84. The magnetic gap of the upstream part of the UE56ID3R is closed to 16.7 mm and the 6 Tesla WLS is running.

The lattice contains strong sextupole magnets, a few skew quadrupole magnets, and obviously the lattice symmetry is broken. The octupole component driving the 4·Q_y-resonance is probably the result of a feed-down from the decapole of the dipole magnets and not a quadrupole fringe field effect. In the Coulomb loss rate the Q_x-Q_y-resonance is only visible because the large horizontal emittance of Coulomb scattered particles is coupled on the resonance into the vertical plane, where the particles get lost on the aperture restriction. Generally, because of the tune shift with amplitude, Coulomb losses show strong asymmetries and hysteresis effects.

In the loss rate related to Touschek scattered particles 3 difference coupling resonances show up. On a coupling resonance the horizontal emittance is coupled to the vertical plane, the particle density drops, and the loss rate goes down. The Q_x-Q_y-resonance is the most dominating one. The reduction of the Touschek losses on this resonance, where the Coulomb loss rate increases, demonstrates nicely how these BLMs discriminate the loss mechanisms. Also on the nominal working point, Touschek scattered particles are not primarily lost in the vertical plane opposite to what was observed at the ESRF[6].

Tune scans and the observation of loss rates are very helpful in order to investigate the impact of non-linearities on beam dynamics. Interpretation of the results is simplified if a good selectivity of the beam loss monitors to the different loss mechanisms can be achieved. In certain cases the dominating loss mechanism can be found and the effect of counter measures can be verified easily with BLMs.

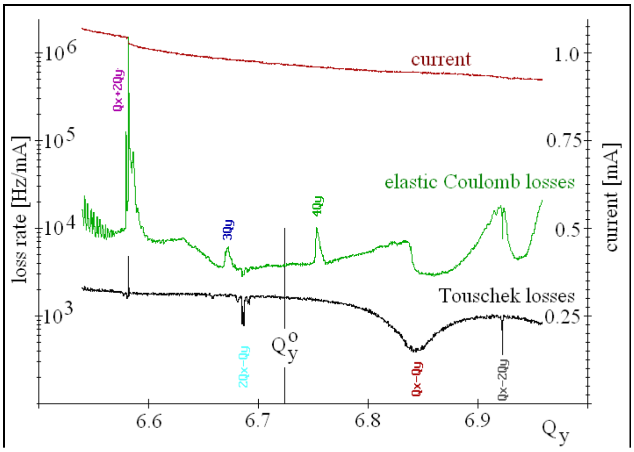

Fig. 3: Comparison of Coulomb and Touschek scattering related losses measured with 1mA stored in a single bunch. The horizontal tune was kept fixed at its nominal value and the vertical tune was varied.

5 EXPERIMENTS WITH LOSS MONITORS SENSITIVE TO TOUSCHEK LOSSES

Touschek scattering and the rate of related losses depend on the density of particles in the transverse and longitudinal phase space and depend in addition on the spin orientation of the colliding particles. Transfer function type experiments have been performed which exploit these sensitivities of the Touschek effect.

In these experiments, the beam is excited by a sinusoidal, time varying external force and the loss rates are monitored as a function of the frequency which is swept slowly back and forth over the region of interest. The observed resonant effects have been used for the determination of the energy, the investigation of the mechanisms which turn the coherent excitation into an incoherent and sometimes desired blow-up of the beam, and the detection of coherent head-tail modes.

5.1 Accurate Determination of the Energy

Historically, at BESSY, the spin sensitivity of Touschek scattering was used very early for the energy measurement of the stored electron beam[7]. In the experiment, BLMs tailored for a high sensitivity to Touschek scattered particles, are used as polarimeter. An increase of the loss rates is observed if the ensemble of electrons is depolarized. This occurs resonantly at a certain frequency of the radial field and from the resonance frequency the average energy of the beam can be determined with high accuracy.

Lately the energy was measured routinely during the normal user runs in order to investigate the intrinsic

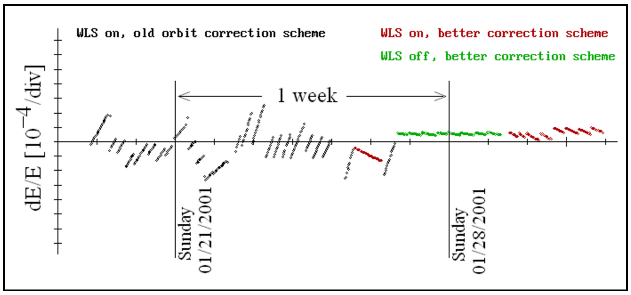

Fig. 4: Relative variations of the energy of the stored beam over 2 weeks measured with the help of BLMs. The automated slow orbit correction is running and for the colored traces a modified algorithm was used.

energy stability of the storage ring[8]. As seen in Fig. 4, the modification of the automated closed orbit correction algorithm has improved the stability of the energy further[9]. Nevertheless, the superconducting wavelength shifter (WLS), running in the so called persistent current mode, still introduces larger drifts of the energy.

The determination of the energy based on the technique of resonant spin depolarization in combination with spin sensitive beam loss monitoring can be applied at most synchrotron light sources if fast vertical feedback kicker magnets are available in order to depolarize the beam. This was done at the ALS and has been used to measure the momentum compaction factor[10].

5.2 *Emittance Dilution*

Third generation light sources, with their low natural emittance and their small emittance coupling ratio, especially operating with high currents per bunch, suffer from high Touschek scattering loss rates and the resulting lifetimes are rather short. Under these circumstances it is quite common to reduce the particle density and sacrifice brilliance in order to gain longer lifetimes. At BESSY the mechanisms of density reduction have been investigated with BLMs. In this study different ways were found how an external coherent excitation can be used for blowing up the beam[11].

There are other possibilities to dilute the emittance. Often the coupling is increased by skew quadrupole magnets or tunes are chosen close to the Q_x-Q_y-coupling resonance. A similar type of resonance can be created by an external time varying skew quadrupole field with a corresponding resonance condition. This was observed in the Touschek loss rates during the spin depolarization experiments indicating that the depolarizing radial field contains an additional skew quadrupole field component. The four striplines, two on the top and two on the bottom of the vacuum chamber, form an ensemble which can create this field component quite naturally.

5.3 *Coherent Head-Tail Modes*

In collaboration with E. Plouviez from the ESRF an attempt was made to selectively excite and detect, with the help of beam loss monitors, the lowest head-tail modes, where head and tail of the bunch move, for example vertically, 180° out of phase. This mode of oscillation can be created if the beam is excited resonantly over many turns such that head and tail always experience kicks in opposite directions. Stripline kickers will do this, if driven by an amplitude modulated high frequency voltage at 250 MHz, locked to the RF master oscillator. The phase of the excitation can be chosen such, that either all particles inside the bunch experience the same kick and dominantly the rigid dipole mode, m=0, is excited, or, with the phase shifted by 90°, the head and the tail of the bunch are kicked in opposite directions and preferentially the m=±1-modes are excited. According to simulations of the latter case, the particle density inside the bunch should be reduced on average if the coherent head-tail mode is excited. The resonant density reduction leads to a smaller Touschek scattering rate which can be detected easily.

In Fig. 5 the effect of a selective excitation of the head-tail modes in the vertical plane on the loss rates, the vertical beam size, as measured with the X-ray pinhole camera[12], and the beam current is shown. The head-tail modes show up very clearly in the Touschek loss rates and the vertical beam size. Not shown here is the trace recorded on the spectrum analyzer whose tracking generator was producing the frequency ramp. No signs of the head-tail modes can be seen in the center of mass motion of the ensemble of particles since the vertical chromaticity was set to zero.

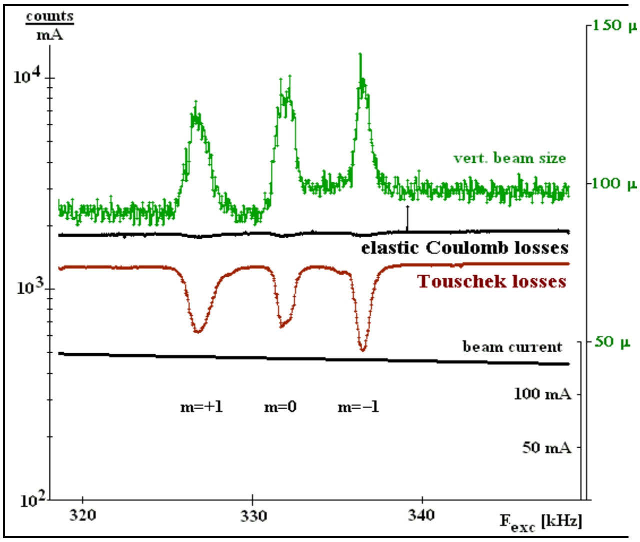

Fig. 5: Touschek (red), elastic Coulomb (black) loss rates, and vertical beam size (green) measured as a function of the frequency used for the modulation of the amplitude of the beam exciting 250 MHz voltage. Dominantly the head-tail modes m=±1 are excited.

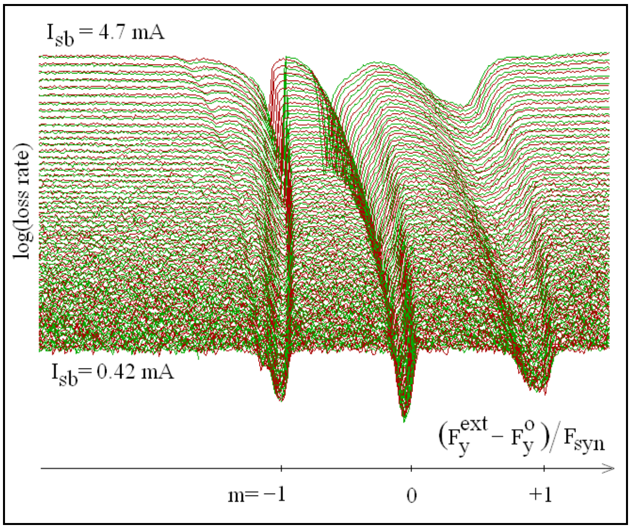

Fig. 6: Head-tail modes as a function of current in a single bunch at zero chromaticity. The head-tail modes were excited with the technique described in the text. Note the strong broadening of the m=+1-mode, the small line emerging from the m=-1-mode, and the hysteresis effects of this mode between up- and down-scans (green and red curves) at higher beam currents.

This technique was used in order to investigate the current dependence of these modes as a function of single bunch beam current at zero chromaticity. The result is shown in Fig 6. Under these conditions a clear observation of the coherent head-tail modes is not possible with the conventional approach of looking at the center of mass motion and without strong coupling of the head-tail modes to the rigid dipole mode. However, these exper-iments are relevant for a better understanding of the head-tail instability and the role played by the longitudinal dynamics in this, often current limiting, instability.

The selective excitation and beam loss monitoring as a means to detect coherent head-tail modes should be applied on other storage rings in order to find out whether the observations are similar to BESSY II: Strong broadening of the m=+1-mode, the small line emerging from the m=-1-mode at rather low single bunch beam current, and the non-linearity which shows up in the hysteresis between the up- and down scans. These observations are unexpected and theory does not yet give an explanation.

6 CONCLUSION

The use of beam loss monitors in storage rings opens a wide field of challenging experiments. Tune scans and Coulomb related loss rate detection leads to a better understanding of the lattice or insertion device induced non-linearity. Transfer function type experiments in combination with monitoring the Touschek related losses opens a new field of experiments especially if more complex ways for the excitation of the beam are chosen.

The observation of the head-tail modes with beam loss monitors will hopefully improve the understanding of the related instabilities.

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