Ion Trapping Investigations in ELETTRA

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Abstract

The experimental results of ion trapping phenomena observed in the ELETTRA storage ring are present. A comparison is made with theoretical predictions.

1. INTRODUCTION

The Italian third generation light source, ELETTRA, started its period of commissioning in October 1993, although still in its commissioning phase the facility is providing light for experiments [1]. The facility uses electrons as its source of radiation. Ion trapping associated with the use of electrons is well known, in theory, and in a few existing machines experimentally. The phenomena of ion trapping in ELETTRA is presented here. The paper covers two topics: the trapping of ions and the instabilities produced by their capture. The elusive and unpredictable nature of ion trapping makes systematic study of the effects difficult to perform. Measurements were taken of the betatron frequencies, lifetime, transverse beam sizes and low frequency transverse beam oscillations as a function of current and filling pattern.

2. THE OBSERVATIONS

The observations reported in this paper were made at 1.1 GeV. Theses were: a positive increase of the tunes in both planes as a function of increasing beam current, low frequency transverse beam oscillations which are current dependent, transverse beam growth and vertical beam blow-up as a function of current and filling pattern and changes in lifetime. The most convincing evidence of ion trapping comes from the vertical increase of the beam size triggered by an external source, the tune measurement system. The increased beam dimensions traps more ions which maintains the large beam size. Shaking the beam with the kicker magnets the ions are then cleared. Once the kickers are switched off the beam returns to its original size before the blow-up. Another manifestation is seen close to the vertical beam blow up (which is seen as a violent shaking of the beam) when making careful tune measurements with minimal excitation of the beam from the striplines. Whenever the beam spontaneously starts to vibrate the tune signal shows a strong peak up to 4 kHz below the signal for the non-vibrating beam which is still weakly present. This can be explained by a clearing and recapture of the ions with consequent shifts in the betatron frequency.

3. THE TRAPPING MECHANISM

The trapping of ions is principally determined by the beam current, the transverse beam dimensions and the homogeneity and filling pattern of the storage ring. Large beam sizes, low currents and homogeneous filling of the ring favour the capture of ions down to the smallest ion masses. For a given set of the above mentioned machine parameters a critical mass is defined by the linear theory of ion trapping above which all ion masses are trapped [2]. In reality, though, the natural non-uniformity of the bunch to bunch filling and the presence of non-linear forces define stable mass bands that break up the continuum. The bands are further separated and diluted when a gap is introduced into the bunch train. The behaviour of the number of ion masses trapped as a function of gap and beam current is schematically shown in figure 1. The figure shows that an increase in current leads to a reduction of mass numbers trapped. A greater probability exists for the trapping of heavier masses.

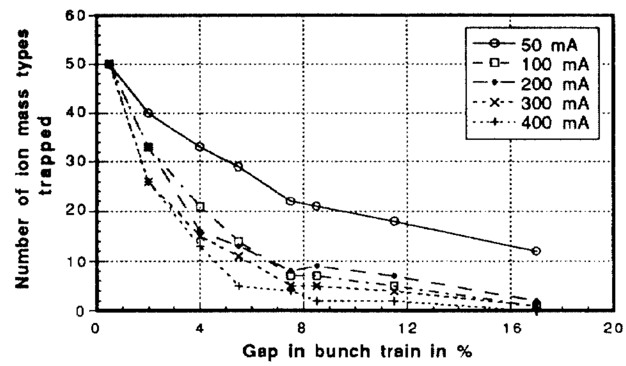

Figure 1. Computed dependence of the number of ion masses trapped as a function of gap in the bunch train and beam current at 2.0 GeV.

For inhomogeneous fills an increase in beam current leads to an increase in the number of ions trapped of a given mass, however, it also leads to a larger separation and dilution of the stable mass bands especially for the smaller masses. An increase in current can therefore lead to sudden loss of a specific mass number, with an associated decrease in the focusing effect of the trapped ion-cloud. For current intervals where no ion mass number losses occur, the increase in beam current will lead to an increase in trapping and associated focusing. In addition the increase in beam size due to trapping must be taken into account. The increase tends to favour larger stable mass bands for the same current. Once trapping is underway a beam blowup occurs which allows the containment of an ion mass which would otherwise be unstable at the same current, leading to a positive feedback for trapping. From these considerations both an increase and a decrease in tune may be observed, depending on the machine condition (vacuum partial pressures, filling etc.), as a function of current.

For fairly homogeneous complete fills, the vertical tune initially increases and then decreases as a function current. In these cases there is a saturation in the injection process at the highest currents, which are always less than when operating with a partial filling. The saturation point is usually characterised by a violent shaking of the beam in the vertical plane. The increase in tunes is explained by the increased number of captured ions due to the higher beam current. The decrease is explained by the eventual loss of ions due to over focusing corresponding to an increase in the critical mass in association with the increase in current. Particular care has to be taken in making the tune measurements since the act of exciting the beam for the measurement can itself momentarily interfere with the trapping mechanism and thus invalidate the results.

For machine fills with a small gap or inhomogeneous complete fills, all tune measurements as a function of current have shown an initial decrease in vertical tune followed by an increase, see figure 7. The width of the tune signal increases with current up to the point where the tune increases. The decrease is caused by the change in stable mass bands for increasing currents, with subsequent loss of a given mass number. In the regime of vertical tune decrease the horizontal tune is basically flat, but then increases as the vertical increases.

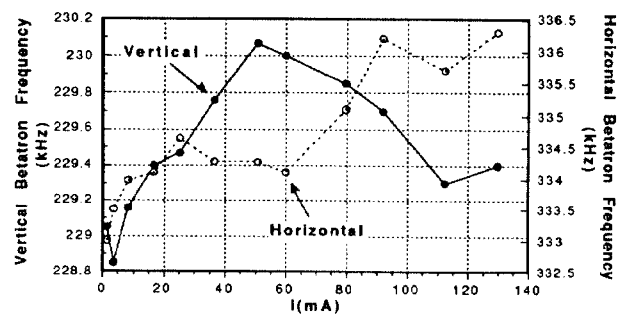

Figure 2. The behaviour of the betatron frequencies as a function of current for a complete homogeneous filling.

The beam size as a function of beam current for different ring fillings is shown in figure 3. For 100% filling the transverse size increases smoothly up to a blowup threshold, when the beam vigorously shakes in the vertical plane. For the situations where a small gap is introduced in the bunch train the increase in beam size is not as noticeable and the threshold for the blowup occurs at much higher currents. Once the beam is blown up, switching on the fast kicker magnets tends to calm the oscillation which after a while starts again.

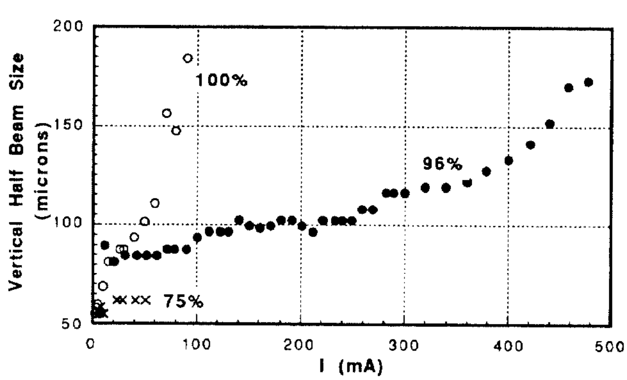

Figure 3. Comparison of vertical beam half size as a function of beam current for three different machine fillings: 100, 96 and 75%.

4. THE INSTABILITIES

All of the ion trapping observations at ELETTRA have been associated with low frequency beam oscillations (LFO). These oscillations have been observed on the Synchrotron Radiation Profile Monitor (SRPM) and quantified on various pickups: BPM's, button electrodes and strip lines. Depending on the beam current the instability is seen on the synchrotron radiation profile monitor as a vigorous vertical oscillation or occasional pulsation. Figure 4 shows the signal from the SRPM slightly before and after the threshold.

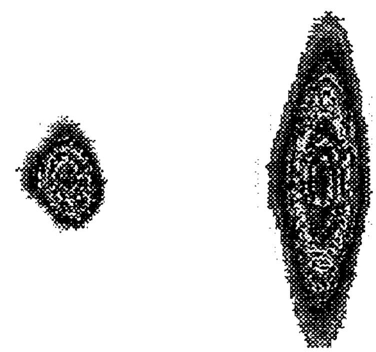

Figure 4. Synchrotron radiation profile just before and after the vertical beam blow-up threshold.

An examination of the spectral content of the transverse low frequency oscillations reveals signals in the range of 0.1 to 50 Hz. These signals are also present, albeit weaker, when the beam is not visibly shaking. The oscillations are present at low currents, < 2 mA, whereas the beam throbbing starts at higher currents. The SRPM is positioned at a point of low horizontal dispersion and a vertical beta four times the machine minimum (see below). The dependence of the frequencies with current is roughly linear, with more frequencies apparent at low currents. The measured low frequency modes are shown in figure 5. The linear behaviour for the modes is in agreement with observations made at the Photon Factory [3].

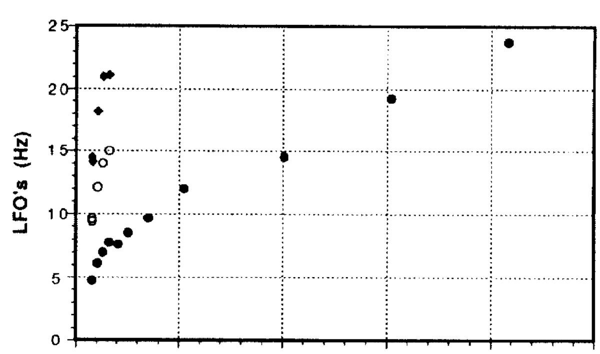

Figure 5. Frequency dependence of the beam oscillations (LFO's) as a function beam current.

As the current is increased a single signal dominates, and its dependence with current changes at a certain value. This value has a tendency to occur when the vertical tune shift changes direction and the lifetime improves. Again, a possible explanation can be given by the change in ion mass types trapped by the beam as the current is increased, since this would change the dynamics of the throbbing mechanism.

To see if the observed LFO's could possibly be explained by the throbbing of the electrons with the ion cloud, some estimates were made with the two macro particle model concerning their dipolar motions [4]. The model simply describes the coupled harmonic oscillations of the two particles influenced by the extra restoring force due to the presence of the other. The theory explains that under certain conditions, stable oscillations having frequencies of the order of the revolution period become unstable, leading to ion loss whilst the electrons increase their oscillation amplitude until damped. The whole process, which is observed as a low frequency throbbing, is repeated since the damped electrons recollect the ions. The estimates (figure 6) made for ELETTRA indicate that, due mainly to the smallness of the beam size which enhances the effect, the threshold current for the throbbing comes out to be considerably low which is in accordance with the observation, even with the assumed value of 5×10^{-3} for the neutralisation factor and 50% betatron coupling.

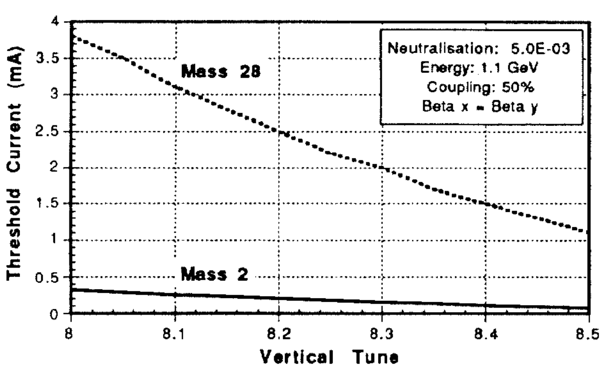

Figure 6. Throbbing threshold current as a function of tune.

As a function of ring filling, the principal frequencies shift to lower values, and disappear completely for bunch trains with a gap of ~60%.

The beam blow-up is furthermore influenced by multi-bunch instabilities. Several spectral observations have been made of the transverse low frequency oscillations of the beam. The oscillation strengths strongly depend on the temperature of the cavities. Cavity tuning is made by varying the temperature which moves the higher order modes with respect to the fundamental. At those temperatures where a multiple of the revolution frequency is close to a longitudinal higher order mode [5], the oscillation strengths increase by two orders of magnitude, and the frequencies values of the signals decrease. This may be explained if the spurious vertical dispersion (~4 cm) in the machine is taken into account. The modes of the longitudinal multibunch instability change the transverse distribution of the electron bunches as seen by the adiabatically moving ion cloud, with a corresponding effect on the ion cloud electron bunch throbbing. An estimated $\Delta E/E$ of ~1.0% associated with the instability would change the vertical beam size at the point of minimum beta by an order of magnitude. This point would also be the most likely origin for the ion-cloud electron beam throbbing, given the increased focusing there. Its expected that once the spurious dispersion is corrected the low frequency oscillations will be greatly reduced.

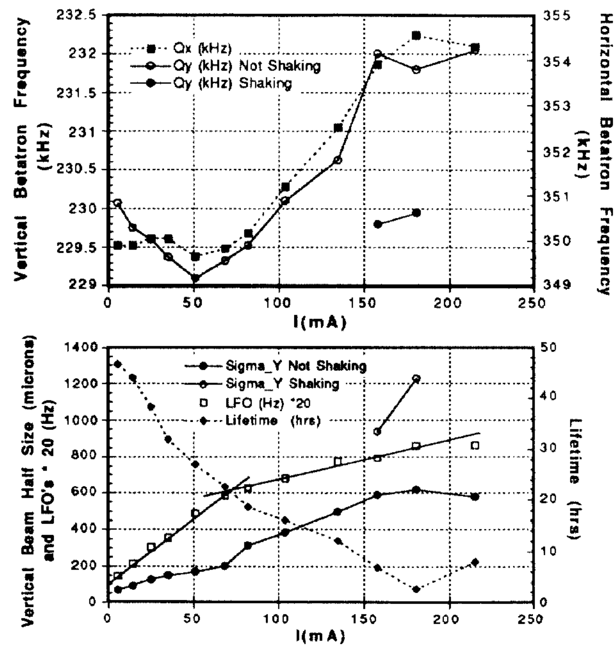

Figure 7. Comparison of betatron frequencies, half-beam size, lifetime and LFO's for a complete inhomogeneous filling. The figures also show the decrease in betatron frequency and increase in beam size when the beam starts to shake.

5. CONCLUSIONS

The first results of ion trapping related phenomena observed at ELETTRA have been reported. General trends of observations with tentative explanation of the results have been given. Although serious for a light source, the harmful consequences of ion trapping can be avoided by a partial filling the storage ring. Furthermore, normal machine operation [6] is at a higher energy where ion effects are reduced. Compensation of the spurious horizontal and vertical effective beam emittance will further improve the situation. Further machine studies are needed for a clearer understanding of the influence of the inter-related machine parameters.

7. REFERENCES

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