AN INCREASING OF ELECTRON BEAM LIFETIME AT INJECTION ENERGY IN SIBERIA-2 STORAGE RING BY REGULATING OF BETATRON COUPLING

A.Valentinov, V.Korchuganov, Yu.Krylov, Yu.Yupinov, RRC Kurchatov Institute, Moscow, Russia

Abstract

A dedicated synchrotron light source SIBERIA-2 operates at 2.5 GeV with more than 100 mA electron current. An electron beam lifetime at this energy is defined now by vacuum conditions and exceeds 15 hours for 100 mA. The lifetime at injection energy 0.45 GeV is much lower – less than half an hour for typical current value 3 – 4 mA in singlebunch mode.

An analysis of the lifetime value displayed a strong influence of Toushek effect in a presence of a horizontal aperture limitation. A dependence of the lifetime on different parameters (RF voltage, horizontal geometric and dynamic aperture, bunch current, betatron coupling value, electron energy) was analyzed.

A betatron coupling regulation was recognized the easiest way to increase lifetime value at injection energy. It was done by two families of skew-quadrupole lenses. A 30 – 40% increasing of the lifetime was observed for different values of a total current. Also a storing speed was raised because of slower decreasing of a stored current. The beam lifetime during energy ramping was also increased. It led to decreasing of current losses from 5 - 6% to 1.5 – 2% during energy rising from 0.45 GeV to 2.5 GeV.

INTRODUCTION

A dedicated synchrotron light source SIBERIA-2 [1] operates at 2.5 GeV with 100 – 150 mA electron current. An electron beam lifetime at this energy exceeds 15 hours for 100 mA that is quite enough for SR users. However the lifetime at injection energy 450 MeV is much less and not exceeds 30 minutes for typical current value 5 mA in singlebunch mode. It takes more than 30 minutes to reach 150 mA level, so current losses because of low lifetime during injection process strongly decrease injection speed. Low lifetime value is observed also at the beginning of energy ramping. It leads to additional current losses during this process. For these reasons methods of beam lifetime increasing at injection energy would be very useful. A regulation of betatron coupling is one of such methods.

BEAM LIFETIME AT 2.5 GEV

Beam lifetime $\tau(t)$ at 2.5 GeV depends on time t after energy ramping as follows:

$$\frac{1}{\tau(t)} = \frac{1}{\tau_0} + C \cdot I(t) \qquad (1)$$

where I(t) is electron current, τ_0 is lifetime for beam current close to zero and C is a constant. τ_0 is determined by vacuum level without the beam. Second term in (1) may be determined by Toushek effect or by SR stimulated gas desorbtion from vacuum chamber walls. In our case second effect is working because values of τ_0 and C depend on current integral at 2.5 GeV. This dependence continues at least to 300 A·hours.

The Toushek lifetime depends on many parameters (2):

$$\frac{1}{\tau_{Toushek}} \propto \frac{C(\zeta) \cdot I}{\gamma^3 \cdot \sigma'_x \cdot (\varepsilon_{acc})^2 \cdot V} \qquad (2)$$

where C(ζ) is a function of $\zeta = \left[\frac{\varepsilon_{acc}}{\gamma \sigma'_x}\right]^2$, I is bunch current, γ is relativistic factor, σ'_x is RMS horizontal angular spread, V is proportional to bunch volume: $V \propto \sigma_x \sigma_z \sigma_s$ ($\sigma_z \propto \sqrt{\frac{\varepsilon_z}{\varepsilon_x}} = \sqrt{k}$, $\varepsilon_{x,z}$ – horizontal and vertical emittances, $\sigma_{x,z,s}$ – RMS bunch sizes, k – betatron coupling coefficient), ε_{acc} is the smallest of the physical, dynamic and RF acceptance. Energy acceptance is determined by total RF voltage V_{RF}. If physical aperture X determines ε_{acc}, it will obey to $\varepsilon_{acc} = X/\eta_x$ (η_x – a dispersion function on aperture limitation azimuth). Because τ depends on machine functions it should be calculated as an average value around the ring.

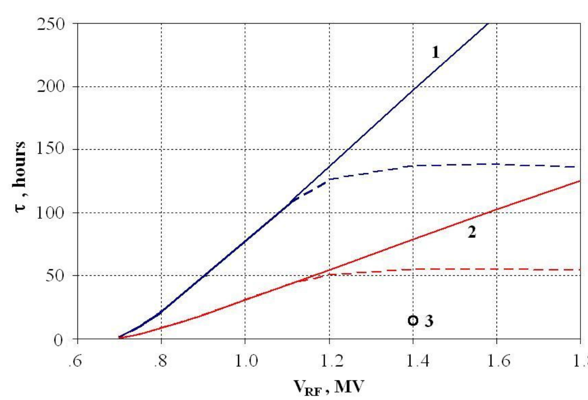

Figure 1: Calculated Toushek lifetime at 2.5 GeV as a function of the total RF voltage V_{RF}. Plots are given for two values of bunch current: **1** - 2 mA, **2** – 5 mA. An influence of horizontal aperture limitation X =20 mm is shown by dashed lines. A coupling coefficient k is equal to 0.01 (close to real value). **3** – measured lifetime value for 2 mA average bunch current and 80 A·hours total integral at 2.5 GeV.

In general, Toushek lifetime τ for particular energy and particular magnetic structure depends on four parameters: bunch current I, total RF voltage V_{RF}, coupling coefficient k and aperture limitation X. At 2.5 GeV transverse bunch sizes are independent on I, so for given V_{RF} and X Toushek lifetime is proportional to $\sqrt{k}$ and inverse proportional to I.

The Toushek lifetime calculations give mush more values than we observe in a real life. The calculations must take into account horizontal aperture limitations. In our case a distance 20 mm from injection septum to ideal orbit is a geometric limitation. A good gradient region in quadrupole lenses has slightly more dimensions. Fig.1 demonstrates theoretical dependence of the Toushek lifetime on V_{RF} for typical beam parameters.

BEAM LIFETIME AT 450 MEV

Only one bunch is added to beam for one injection cycle in SIBERIA-2. Maximal bunch current may be more than 8 mA, but it usually does not exceed 5 mA. Its value is limited by operation of booster storage ring SIBERIA-1 and stability of SIBERIA-2 RF system.

A time interval between injection cycles equals to 30 – 40 seconds. Total beam current is regulated by number of bunches. It takes 40 – 50 injection cycles to store 150 mA (number depends on injection system stability). Maximal value of total current now is determined now by RF system condition. In order to eliminate multibunch instabilities we are forced to increase V_{RF} from initial value of 200 kV up to 300 – 350 kV at the end of storing. It leads to lower injection efficiency, so average bunch current decreases during storing procedure. First bunches loose electrons because of low lifetime value. As a result the average bunch current decreases from 5 mA down to 3 - 4 mA during storage.

Beam lifetime at injection energy is determined by a number of effects such as elastic and non-elastic scattering on residual gas, Toushek effect, quantum effect due to radiation, ion storing on a beam trajectory. On SIBERIA-2 we don't see any dependence of the lifetime on vacuum conditions and outgassing duration (except the very beginning of this process). Calculated values of the lifetime due to Toushek effect were found to be very close to measured ones – from 20 to 30 minutes for 5 mA bunch.

At 450 MeV an intrabeam scattering leads to growth of energy spread and horizontal emittance with increasing of bunch current I. It makes an influence of physical/dynamic aperture limitation stronger at injection energy.

A dependence of the Toushek lifetime τ on four main parameters was analyzed for 450 MeV in order to increase τ. A value of aperture X was recognized to have the strongest influence to τ. (see Fig.2). τ is proportional to $X^{2.62}$ near X value close to 20 mm. Unfortunately we cannot increase the value of X, it is determined by distance from injection septum magnet to an ideal orbit.

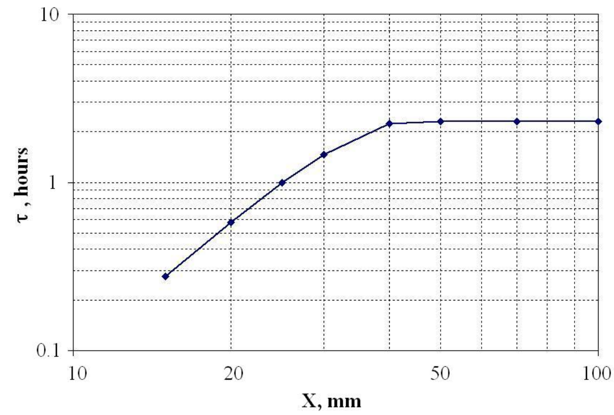

Figure 2: The Toushek lifetime at 450 MeV as a function of horizontal aperture limitation X. I = 5 mA, V_{RF} = 200 kV and coupling k = 0.01.

The RF voltage V_{RF} has weaker influence to the lifetime value. For I = 5 mA and 30 – 300 kV range of V_{RF} we observe $\tau \sim V^{1.2}$. However we see strong τ dependence on X value (Fig.3). As a result Toushek lifetime is almost constant in the 80 – 300 kV range with slightly decreasing to 300 kV.

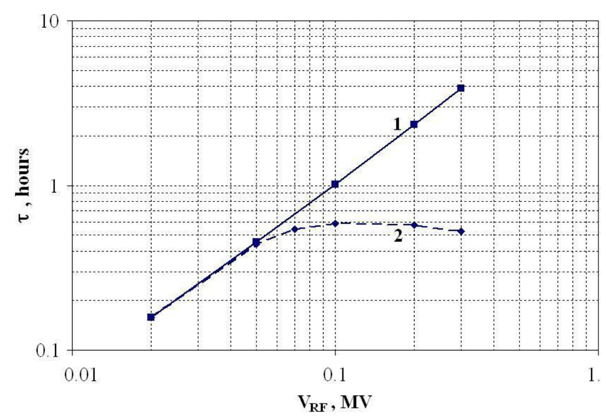

Figure 3: The Toushek lifetime at 450 MeV as a function of RF voltage V_{RF} for I = 5 mA and coupling k = 0.01 with X = ∞ (1) and X = 20 mm (2).

A dependence of τ on bunch current is shown on Fig.4 for V_{RF} = 200 kV and coupling k = .01 in a range 1 – 10 mA. Here $\tau \sim I^{-0.43}$ and we see strong influence of X parameter. It seems we can increase lifetime by decreasing average bunch current. But RF harmonic number of SIBERIA-2 equals to 75. 1 mA average bunch current will correspond to only 75 mA, in addition the storing process become longer. Bunch current of 3 – 5 mA seems a good compromise between beam stability and speed of storing.

The last parameter, betatron coupling k, has the weakest influence to τ: $\tau \sim k^{0.25}$ (see Fig.5). However it is the only one that can be regulated within sufficiently wide range.

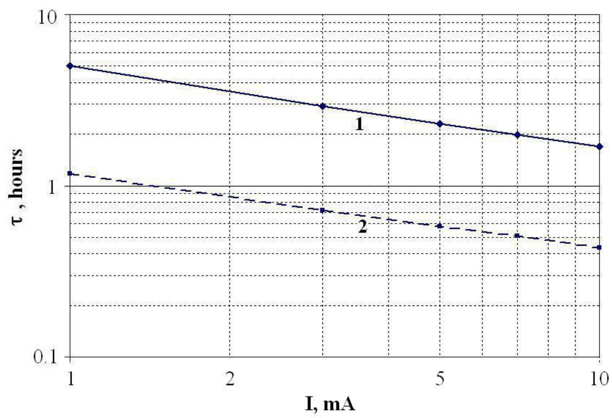

Figure 4: The Toushek lifetime at 450 MeV as a function of bunch current I for V_{RF} = 200 kV, coupling k = 0.01 with X = ∞ (1) and X = 20 mm (2).

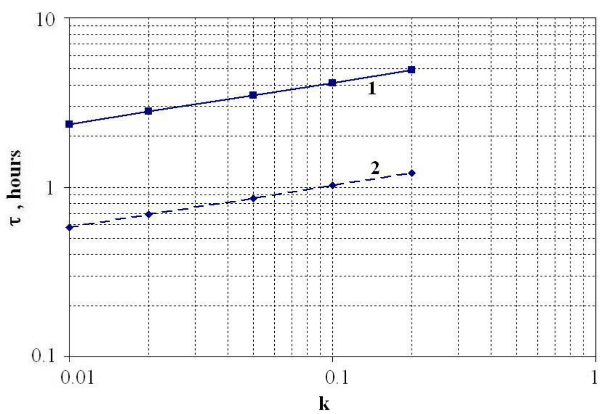

Figure 5: The Toushek lifetime at 450 MeV as a function of betatron coupling k for I = 5 mA and V_{RF} = 200 kV with X = ∞ (1) and X = 20 mm (2).

BETATRON COUPLING REGULATION

Two skew-quadrupole families are provided to regulate betatron coupling in SIBERIA-2. At 2.5 GeV they can decrease coupling coefficient k down to less then 0.001. Vertical emittance is determined by nonzero vertical dispersion in this case. At injection energy coupling is equal approximately to 0.01 without skew-quadrupoles. We can reach coupling value more than 0.3 but it causes too strong betatron tune shifts. Limiting tune shifts by 0.01 we achieve coupling coefficient value k = 0.15. It should increase lifetime approximately twice.

A behavior of lifetime value with increasing of bunch number should be mentioned here. Then number of bunches grows multibunch interactions appear. It leads to higher amplitude of energy vibrations inside every bunch. As a result energy spread becomes higher, effective density of electrons decreases and lifetime value grows even for constant average bunch current. In order to eliminate dangerous amplitude of such vibrations we are forced to increase V_{RF}. This action limits injection efficiency. So, we have several processes during storing: increasing of V_{RF}, decreasing of average bunch current, lifetime growing due to bunch-to-bunch interactions. The last effect is strong enough – lifetime value at the end of storing may be more than twice higher than at the beginning.

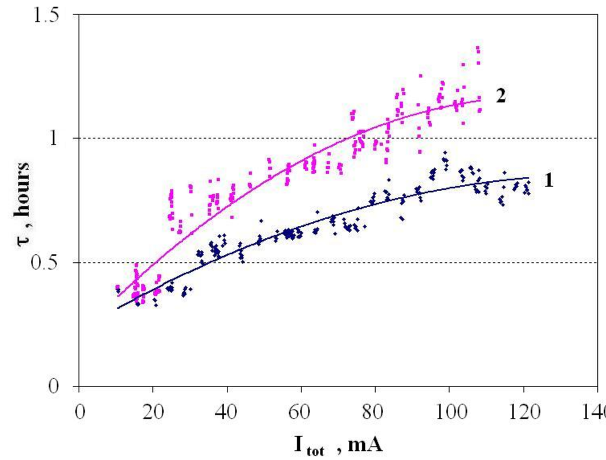

Figure 6: A measured beam lifetime at 450 MeV as a function of total electron current. 1 – without skew-quadrupoles, 2 – with skew-quadrupoles switched on.

Fig.6 demonstrates a lifetime dependence on total current during storing when skew-quadrupoles are switched off (1) and switched on (2). One may see sufficient growth of the lifetime after increasing of a betatron coupling. It achieves 30 - 40% for big number of bunches. It means shortening of the storing procedure because of slower depopulation of the stored current. The increasing of the lifetime turned out less than it was predicted. It indicates a presence of different sources of the lifetime limitation except Toushek effect.

An achieved result is useful also for energy ramping procedure. The calculated Toushek lifetime demonstrates minimum value at 700 MeV region for constant V_{RF}. The value of τ in this minimum is approximately 20% lower than at the injection energy. So the increasing of lifetime leads also to decreasing of current losses during energy ramping. It has allowed reducing such losses down to 2% from initial value 5 – 6%.

CONCLUSIONS

The analysis of the Toushek lifetime at injection energy in SIBERIA-2 storage ring lead to a conclusion of a possibility to increase the lifetime by betatron coupling regulation. As a result we could increase the lifetime on 30 - 40%. It has permitted to accelerate injection procedure because of slower current losses during storing. It also has led to lower losses during energy ramping. Their level has decreased from 5 - 6% down to 2%.

REFERENCES

[1] V.Korchuganov, M.Blokhov, M.Kovalchuk et al. “The status of the Kurchatov center of SR”, *Nuclear Instruments and Methods*, A 543 (2005) pp. 14-18.