SYNOPSIS

Electrons travelling at a relativistic speed and forced to change the direction of their motion under the influence of magnetic field emit electromagnetic radiation with peculiar characteristics known as synchrotron radiation. These electromagnetic radiations cover a wide range of photon energies from the infrared to hard X-ray regions of electromagnetic spectrum. The sources of these radiations are high energy electron or positron circular synchrotrons or storage rings. The storage rings designed specifically for the production of synchrotron radiation across the world such as Diamond light source (U.K.), Soleil (France), Australian light source (Australia) and Indus-2 (India) are known as synchrotron radiation sources. The motion of electrons in a synchrotron or storage ring is guided by an external magnetic field created by periodic arrangement of dipoles, quadrupoles and sextupoles magnets whereas it gets acceleration or the compensation of energy lost due to the emission of synchrotron radiation from an external electric field created by radio frequency (RF) cavities.

In an electron storage ring like Indus-2, the electrons are confined within bunches inside a vacuum chamber. The number of stored bunches in a storage ring may be equal or less than the available RF buckets. The number of maximum RF buckets in the ring is equal to the ratio of the resonant frequency of RF cavity to the revolution frequency of electrons. The electrons which are confined within a bunch execute betatron oscillations about the closed orbit in transverse planes and also execute synchrotron oscillations with respect to synchronous electrons in longitudinal plane. The electrons within a bunch are scattered due to coulomb repulsion with each other and also get scattered due to the interaction with residual gas atoms present in the vacuum chamber. Due to the scattering of electrons within a bunch and with residual gas atoms, electrons are deflected and also undergo changes in energy
which cause an increase in amplitude of betatron oscillations and are lost from the bunch either due to the aperture limitations in transverse plane or due to momentum aperture limitations either in transverse or in longitudinal plane. So the study of the aperture in a storage ring is essential for the estimation of beam lifetime. The experimental studies and theoretical analysis of beam lifetime of stored electrons in Indus-2 storage ring are the objective and scope of the thesis.

The stored electrons orbiting in an electron storage ring may be lost due to various causes. For a well designed storage ring, there are two main classes for electron losses, first is the loss due to scattering and another is the loss due to beam instabilities. While the electron losses due to scattering with other particles is a single particle effect leading to a gradual loss of electrons from the electron beam whereas electron losses due to beam instabilities is a multi particle effect and later can lead to a partial or complete loss of electron beam. This work is mainly focused on the gradual loss of electrons which are mainly due to beam-gas scattering and electron-electron scattering within a bunch known as Touschek scattering. The lifetime $\tau_e$ of stored electron beam during beam current decay is estimated as $-I/(dI/dt)$ where $dI/dt$ is the instantaneous decay rate at particular current $I$ at time $t$. The experimental studies and theoretical analysis of beam lifetime of stored electron beam in multi-bunch mode at beam energy 2.0 and 2.5 GeV with stored current 100 mA in Indus-2 was carried out.

The electrons within a bunch are scattered by the residual gas atoms present in the vacuum chamber. The scattering may be elastic or inelastic. In the initial stage of Indus-2 operation, the vacuum pressure in the storage ring increased due to the photo induced desorption of gases from the surface of vacuum chamber caused by the incident synchrotron radiation emitted by the circulating electron beam. The pressure in the ring gradually reduced with
time due to the cleaning of the surface of vacuum chamber by synchrotron radiation. The beam current decay data with the reduction in pressure with time was studied and the beam lifetime was found to increase with the reduction in vacuum pressure.

When the electrons are scattered elastically with the nuclei of residual gas atoms, they are deflected and the amplitude of betatron oscillation about the closed orbit is increased and are lost at a location where the available aperture for electron motion is less than the betatron oscillation amplitude. The effect of aperture was studied by conducting beam lifetime experiments without and with closed orbit correction in both vertical and horizontal plane. By minimizing closed orbit distortion in vertical and horizontal plane, there is an increase in available aperture for beam motion and also reduction in vacuum pressure was observed, which resulted into an increase in beam lifetime.

The beam lifetime due to elastic scattering between electrons and nuclei of residual gas atoms depends on the shape of the vacuum chamber. The effect of rectangular and elliptical shape of vacuum chamber on beam lifetime due to elastic coulomb scattering was studied using linear beam dynamics. As the vacuum pressure along the circumference in a storage ring is not uniform so analytical formulations for the shape factor for rectangular and elliptical shape of the vacuum chamber as a function of position along the circumference were developed. The analytical expression of the shape factor for elliptical shape of vacuum chamber as a function of longitudinal position was found to be different than the existing expression. The existing expression for shape factor is obtained by considering electron loss at only one location whereas expression was derived by considering the loss at maximum $\beta_x$ and $\beta_z$ locations which are applicable in modern storage ring. These studies show that the effect of shape on shape factor is much smaller as compared to the values obtained using existing analytical expressions.
The contribution of vacuum lifetime and Touschek lifetime to total beam lifetime was separated experimentally by storing same amount of average beam current uniformly in all 291 RF buckets in first experiment and by filling two-third RF buckets and the rest of the RF buckets kept empty in second experiment. The experimental studies show that the vacuum pressure at the same stored beam current is the same at all Bayard Alpert Gauges (BAGs) installed for vacuum pressure measurement in case of uniformly filled all RF buckets and filling two-third RF buckets and the rest of the RF buckets kept empty. By conducting these experiments, we are able to know whether the beam lifetime is limited due to vacuum or Touschek lifetime.

During electro-electron scattering within a bunch and inelastic scattering between stored electrons and nuclei of residual gas atoms, the energy of scattered electrons changes, if this change in energy is more than the momentum aperture, the scattered electrons are lost from the beam. The limitation of momentum aperture which may be either in transverse or in longitudinal plane was studied by conducting experiments with different RF cavity voltages.

The studies of beam lifetime in single bunch mode in Indus-2 were carried out. The objective of these studies was to study the effect on beam lifetime in electron-electron interaction due to increase in electron density within a single bunch.

The Touschek lifetime varies proportionally with vertical beam size which depends on linear betatron coupling in the storage ring. The measurement of betatron coupling in Indus-2 was carried out using minimum tune separation technique and found to be less than 1%. The vertical beam size obtained using betatron coupling was found to be closely same as the vertical beam size obtained using XRF microprobe beamline in Indus-2.

Long beam lifetimes are desirable for the users of synchrotron radiation sources since it gives higher integrated photon flux, reduce the number of refills necessary and improve the
stability by reducing thermal loading effects due to the varying current. In a low emittance electron storage ring, the beam lifetime is dominated by Touschek scattering within a bunch. Simulation studies were carried out to find the effect of RF phase modulation on bunch length. These studies show that by applying phase modulation in main RF, there is an increase in bunch length that leads to the reduction in Touschek scattering within a bunch. The simulation studies were carried out using particle tracking code ELEGANT.

To know the aperture available for stable motion of electrons in a storage ring, movable beam scrapers are used. The measurements of aperture were carried out using movable vertical and horizontal beam scrapers installed in one of the long straight sections in Indus-2. The objective of these measurements was to find out the minimum aperture requirement for undulators which are planned to be installed in long straight sections and also to find the contributors of beam loss. Using the measured aperture and residual gas pressure, the contribution of beam lifetime due to vacuum lifetime, Touschek lifetime and quantum lifetime was obtained. The values of vacuum and Touschek lifetime were compared with the values obtained using partial bunch fill experiments and found to be closely same. The results of vertical and horizontal beam sizes obtained by moving scrapers towards the beam centre in quantum lifetime limit were compared with the beam sizes obtained using X-ray diagnostic beamline and were found to be nearly same.

The thesis is organized into five chapters. The chapter wise summary is as follows:

Chapter 1: The beam lifetime and acceptances in an electron storage ring

In this chapter, an introduction of Indus-2 storage ring and the dependence of beam loss due to quantum excitation, beam-gas scattering and Touschek scattering will be presented. The acceptance available in the ring i.e. physical acceptance, dynamic acceptance and RF
acceptance will also be summarized. The theoretical estimation of quantum lifetime, vacuum lifetime and Touschek lifetime will also be discussed.

Chapter 2: Dependence of electron loss on the shape of vacuum chamber

As the vacuum pressure in a storage ring is not uniform along the circumference and it varies from place to place. In order to calculate beam lifetime due to elastic scattering between electrons and nuclei of residual gas atoms, the vacuum pressure and shape factor information at all locations in the ring is required. Due to non uniform pressure in storage ring, it is important to know the shape factor as a function of longitudinal position in the ring. Analytical expressions for the shape factor as a function of position along the circumference for rectangular and elliptical shape of the vacuum chamber was derived considering the aperture to be uniform along the circumference and the loss of electrons at the quadrupole locations. The expression given in the literature is for the average shape factors which are not applicable to the practical situations in which the pressure is not uniform at all places along the circumference of ring.

In this chapter, analytical formulations of shape factor due to elastic coulomb scattering between electron and nuclei of residual gas atoms will be presented considering rectangular and elliptical shape of vacuum chamber for Indus-2 storage ring. A comparison in the value of shape factor using existing expressions will also be presented.

Chapter 3: Studies of electron-electron interaction within a bunch

The electrons in a storage ring are confined within bunches. As the density of electrons in a bunch increases, the scattering of electrons within the bunch increases which is known as Touschek scattering. Beam lifetime due to Touschek scattering depends on how strongly electrons are packed within a bunch. It thus depends not only on the beam current but also
upon the beam sizes in horizontal and vertical plane and the bunch length. The vertical beam size which depends on the coupling between the horizontal and vertical motion has been used for the calculation of Touschek lifetime. Linear betatron coupling in Indus-2 was measured using minimum tune separation technique and found to be less than 1%. The vertical beam size obtained using betatron coupling was found to closely agree with the vertical beam size obtained using XRF microprobe beamline in Indus-2. Linear betatron coupling and its measurement using minimum tune separation technique in Indus-2 will be presented.

In a low emittance electron storage ring, the beam lifetime is limited due to Touschek scattering. The Touschek scattering can be decreased by applying phase modulation in main RF system. Simulation studies on the effect of phase modulation of frequency nearly two-times of synchrotron frequency in main RF signal were carried out using particle tracking code ELEGANT. The tracking results of longitudinal phase space and the effect of phase modulation on beam parameters in longitudinal plane i.e. bunch length and energy spread in Indus-2 at beam energy 2.5 GeV will be presented.

Chapter 4: Experimental studies of beam lifetime in Indus-2

a) Experiments using multi-bunch mode

Beam lifetime experiments were conducted to study the effect of aperture on lifetime of stored electron beam. For the experiment, beam current decay was monitored without and with closed orbit correction in vertical and horizontal plane. The results of the effect of closed orbit correction on beam lifetime will be discussed. The increase in beam lifetime with reduction in pressure with time will also be discussed. An equation of beam current decay generated using a least square minimization method that closely follows the beam current decay of stored electron beam will also be discussed.
Beam lifetime experiments were also conducted by storing electrons uniformly in all 291 available RF buckets and also by storing electrons in two third RF buckets keeping rest of the RF buckets empty. The analysis of measured beam lifetime using vacuum pressure and RF cavity voltage was carried out. These results will be presented in this chapter. The results of the effect of bunch fill pattern and RF cavity voltage on beam lifetime will also be discussed. The separation of vacuum lifetime, Touschek lifetime from the measured beam lifetime will also be covered in this chapter.

a) Experiments using single bunch mode

To study the effect of beam energy on Touschek scattering, the beam current decay of equal amount of average current stored in single bunch in one RF bucket out of 291 RF buckets was observed at low beam energy i.e. 550 MeV and higher energy 2.5 GeV. A comparison of beam current decay in single bunch storage mode at these beam energy will be presented.

Chapter 5: Measurement of aperture and beam lifetime using movable beam scrapers

The vertical and horizontal apertures available for the stable beam motion at beam scraper locations were measured using vertical and horizontal movable beam scrapers which are installed in one of the long straight sections in Indus-2. With the movement of vertical and horizontal scrapers, the beam lifetime was measured at different positions of scrapers from the beam centre. By using the measured beam lifetime data with scraper position, the contribution of beam lifetime due to elastic scattering between electrons and residual gas atoms, bremsstrahlung, Touschek and quantum excitation was estimated. The measured value of vertical and horizontal aperture at scraper location was found to be ±4.1 mm and ±12.45 mm respectively at beam energy 2.5 GeV. The measurement and analysis of experimental data will be presented in this chapter.
Summary:

The loss of electrons due to elastic scattering between electrons and the nuclei of the residual gas atoms for rectangular and elliptical shape of the vacuum chamber was studied using linear beam dynamics. Analytical expressions for the shape factors for rectangular and elliptical shape of vacuum chamber as a function of position along the circumference of storage ring were developed. The expressions were derived considering the loss of electrons at quadrupole locations i.e. at maximum $\beta_x$ and maximum $\beta_z$ locations. The expression for shape factor for elliptical shape of vacuum chamber is found to be different than the existing expression because in existing expression the loss of electrons was considered at one location only which is not applicable in modern electron storage ring. These expressions are very useful to estimate the beam lifetime due to elastic scattering of electrons with the nuclei of residual gas atoms in realistic conditions like non uniform vacuum pressure in storage ring. The contribution of vacuum lifetime and Touschek lifetime in measured beam lifetime was separated by storing electrons uniformly in all 291 RF buckets and also storing electrons in two-third RF buckets keeping rest of the RF buckets empty. These studies are very useful to know the limiting factor of beam lifetime i.e. either vacuum lifetime or Touschek lifetime.

The beam lifetime due to a high density of electrons in a bunch was studied by storing the electrons in a single RF bucket out of 291 RF buckets in Indus-2 ring.

The aperture available for stable beam motion in Indus-2 was measured by using movable beam scrapers. These studies are useful to choose an appropriate aperture for undulators which are planned to be installed in Indus-2. From the measured beam lifetime with scraper position from the beam centre, the contribution of beam lifetime due to elastic scattering of electron with the nuclei of residual gas atoms, bremsstrahlung, Touschek scattering and quantum excitation was estimated separately. The vacuum and Touschek lifetime obtained
using scrapers was closely same as obtained using partial bunch fill experiments. The vertical and horizontal aperture studies using movable beam scrapers show that the beam lifetime is limited due to elastic coulomb scattering and inelastic scattering between electrons and nuclei of residual gas atoms. The measured vertical aperture at scraper location was found to be less than from its theoretical estimated value. The vertical aperture was increased by minimizing the closed orbit distortion in vertical plane and resulted into ~40% increase in beam lifetime. The lifetime will further improve by reduction in vacuum pressure. The vertical aperture measurements carried out indicate that the beam lifetime will not be reduced after installation of insertion devices as the vertical aperture available will be ± 8 mm.