T.3: Beam Lifetime Studies in Synchrotron Radiation Source Indus-2

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Abstract:

The loss of stored electrons in Synchrotron Radiation Source (Indus-2) is due to the interaction of electron beam with the residual gas atoms present in the vacuum chamber and also electron-electron interaction within a beam bunch. These losses depend on the transverse and longitudinal acceptances available in ring for stable motion of electrons. In this article, theoretical estimations of physical acceptance and dynamic momentum acceptance of Indus-2 storage ring available for stable motion of electron beam is reported. The aperture available for stable beam motion in vertical and horizontal plane was measured using movable beam scrapers which are installed in one of the long straight sections in Indus-2 ring. The aperture measurements and analysis of collected data are presented. Beam experiments which were conducted to separate the contribution of vacuum and Touschek lifetime from the measured beam lifetime is discussed. The beam lifetime in low emittance electron storage rings is limited due to large angle intra-beam coulomb scattering (Touschek lifetime) within a high density electron bunch. For the enhancement of Touschek lifetime, alternative methods like enhancement in vertical beam emittance and RF phase modulation are also discussed in the theme article.

1. Introduction

When electrons, travelling at a relativistic speed, are forced to change the direction of their motion under the influence of magnetic field, they emit electromagnetic radiation with peculiar characteristics, which is known as synchrotron radiation. The synchrotron radiation covers a wide range of photon energies from infrared to hard X-ray. There are various uses of synchrotron radiation in condensed matter physics, surface physics, chemistry, biochemistry, industry, medical research etc.The sources of the synchrotron radiation are high energy electron or positron circular synchrotrons or storage rings. Some important synchrotron radiation sources in the world are Spring-8 (Japan), ESRF (France), APS (U.S.A), Diamond (U.K.), Soleil (France), Australian light source (Australia), Pohang light source (Korea) and Indus-2 (India), etc.

Indus-2, an electron storage ring, is operational at the beam energy of 2.5 GeV and 200 mA stored current. Photon beams tapped through its various beamlines which are connected to the ports of dipole magnets are in use by synchrotron radiation users. The lifetime of stored electron beam is an important parameter for assessing the performance of any electron storage ring. The lifetime of stored electron beam of 100 mA at 2.5 GeV in Indus-2 ring has been studied by conducting experiments and analysis of the measured data. The studies are presented in this article.

Indus-2, a storage ring [1-2], consists of eight periodic unit cells each of length 21.559 m. A unit cell with all magnets arrangement is shown in Fig.T.3.1.

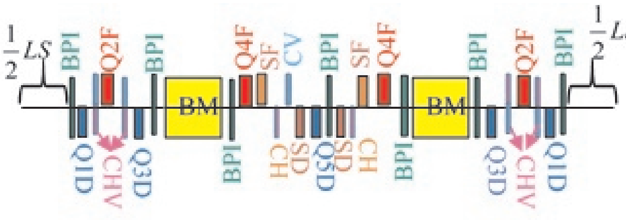

Fig. T.3.1:Unit cell of Indus-2, BM: Dipole magnet; Q1D, Q3D, Q5D: Defocusing quadrupole magnets; Q2F, Q4F: Focusing quadrupole magnets; SF: Focusing sextupole magnets, SD: Defocusing sextupole magnets; CH: Horizontal steering magnets, CV: Vertical steering magnets,CHV: Combined horizontal and vertical steering magnets; BPI: Beam position indicator, LS: Long straight section

Each unit cell comprises of two dipole, nine quadrupole, four chromaticity correcting sextupole, six horizontal and five vertical steering magnets, seven beam position indicators and a 4.5 m free long straight section. So Indus-2 ring has a total of sixteen dipoles, seventy two quadrupoles, thirty two sextupoles, forty eight horizontal steering and forty vertical steering magnets, fifty six beam position indicators and eight long straight sections.

The dipole magnets are used to circulate the electron beam on a design closed orbit path, quadrupole magnets are used to confine the beam towards the closed orbit and sextupole magnets are used for the correction of chromatic aberration (variation in focusing strengths of quadrupole with electron beam energy). Horizontal and vertical steering magnets are used to correct the closed orbit distortion in horizontal and vertical plane respectively. Beam position indicators are used to measure the beam position in horizontal and vertical planes in the ring. Long straight sections are used to accommodate injection septum magnets, four injection kicker magnets, four Radio Frequency (RF) cavities and five proposed insertion devices (two planar undulators U1, U2 and one Advanced Planar Polarized Light Emitter undulator U3 have already been installed in three long straight sections). The periodic arrangement of magnetic elements in a unit cell is known as lattice. The variation of lattice beta functions in horizontal and vertical plane (β_x and β_z) and horizontal dispersion function (η) in a unit cell of Indus-2 ring is shown in Fig. T.3.2.

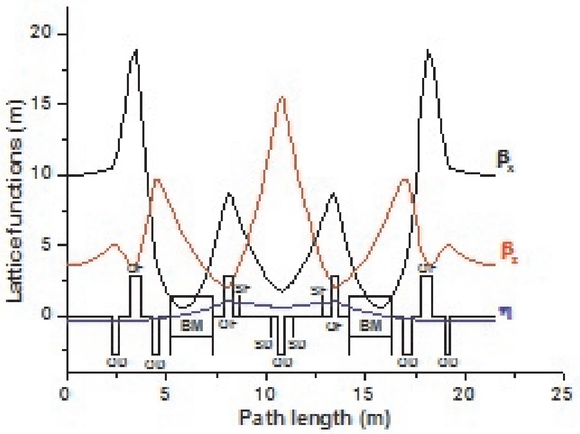

Fig.T.3.2: Variation in lattice functions in Indus-2 unit cell

In electron storage rings, bunches of electrons are confined inside the vacuum chamber [3] having average vacuum pressure of the order of $1\text{x}10^{-9}$ Torr. The number of electron bunches in a storage ring may be equal to or less than the number of available RF buckets. The maximum number of RF buckets in a ring is equal to the ratio of the resonant frequency of RF cavity f_{rf} to the revolution frequency of electrons f_{rev}. There are 291 maximum RF buckets available in Indus-2 and there is a provision to fill electrons in all RF buckets as well as to keep some RF buckets empty. The electrons confined within a beam bunch execute oscillations about the closed orbit in horizontal and vertical plane as well as about the position of synchronous electron in the longitudinal plane. The oscillations about the closed orbit in transverse plane are known as the betatron oscillations whereas the oscillations about the synchronous electron in longitudinal plane are known as synchrotron oscillations. The number of betatron and synchrotron oscillations of electrons in one revolution of ring is known as the betatron and synchrotron tune respectively. For stable motion of stored electron beam, betatron and synchrotron tunes should remain unchanged during the beam current decay.

2. Beam loss mechanisms in electron storage ring

The stored electrons orbiting in an electron storage ring may be lost due to various reasons. For a well-designed storage ring, there are two main causes for electron losses; first is due to scattering and second is due to beam instabilities [4]. 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 the electron beam. The multi-particle effect arises due to electromagnetic interaction of the high intensity electron beam with its wake fields which are induced due to resistive wall of vacuum chamber, broad band impedance and narrow band impedance of the various storage ring components. The broad band impedance of the ring arises due to non uniform cross section of the components in the ring like bellows, kickers and beam position indicators whereas narrow band impedance of the ring arises mainly due to RF cavities. The wake fields due to broad band impedance are short range whereas the wake fields due to narrow band impedance are long range. The wake fields affect the motion of the electron beam transversely or longitudinally. Losses due to beam instabilities are generally very fast. Slow instabilities can be suppressed by natural damping i.e. radiation damping due to synchrotron radiation emission and Landau damping introduced by partial RF buckets fill or efficiently cured by using transverse and longitudinal multi-bunch feedback systems. In Indus-2 transverse multi bunch feedback has been installed and is operational whereas longitudinal multi bunch feedback is to be installed. The longitudinal coupled bunch instabilities are suppressed by optimizing the water temperature in the individual RF cavities.

For measurement of average beam current and beam lifetime in Indus-2, there is a DC Current Transformer (DCCT) installed in one of the long straight sections. The instantaneous lifetime (τ_t) of stored electron beam during beam current decay is estimated as $-I/(dI/dt)$ where dI/dt is the instantaneous decay rate at a particular current I at time t. Long beam lifetimes are desirable for the users of synchrotron radiation since it provides higher integrated photon flux, reduces the number of refills and improve the beam stability by reducing thermal loading effects due to the varying beam current. There are several effects that limit the beam lifetime in electron storage rings [5]. In the absence of beam instabilities, beam lifetime is usually determined by the elastic and inelastic scattering of the electrons with the residual gas atoms [6] known as vacuum lifetime (τ_v) the electron-electron scattering within the beam bunch known as Touschek lifetime (τ_{tous}) and due to quantum excitation known as quantum lifetime (τ_q). The total beam lifetime (τ_t) is defined as

$$\frac{1}{\tau_t} = \frac{1}{\tau_v} + \frac{1}{\tau_{tous}} + \frac{1}{\tau_q}$$

The mechanisms, leading to electron loss, vary for the different lifetime limitations. For the elastic coulomb scattering between electrons and residual gas atoms present in the vacuum chamber, the electrons are deflected and undergo large betatron oscillations. If the oscillation amplitude is larger than the acceptance of the storage ring, the electron will be lost. For inelastic scattering between electrons and residual gas atoms, also known as bremsstrahlung, there is a change in energy of electrons. If the change in energy is larger than the RF acceptance or transverse momentum acceptance, the electron will be lost. If two electrons within an electron bunch collide, there is a transfer of energy from transverse to the longitudinal plane. In large angle coulomb scattering known as Touschek scattering, energy transfer from the horizontal plane to the longitudinal plane are sufficient for loss of both colliding electrons [7]. If the momentum change experienced by the electron exceeds the momentum acceptance of the electron storage ring then the electron will be lost. So the acceptances are the main limitation in all electron storage rings. The apertures of a storage ring are not only defined physically by the vacuum chamber but also by the electromagnetic fields which guide and accelerate the electron beam and keep it confined in six dimensional phase space. In electron storage ring three acceptances i.e. physical acceptance, dynamic aperture and momentum acceptance are considered which are discussed in next section.

3. Acceptances of Indus-2 ring for electron beam

The motion of electrons in a storage ring [8] is described using a coordinate system related to the ideal orbit of the beam. For small deviations from the ideal orbit, the motion of the electrons are described by six dimensional phase space coordinates (x,x',z,z',s,δ). The horizontal motion, perpendicular to the direction of motion of an electron, is described by the horizontal displacement x and the horizontal angular deviation $x'=dx/ds$ from the ideal orbit. Similarly vertical motion is described by the vertical displacement z and the vertical angular deviation $z'=dz/ds$. The longitudinal motion, tangential to the direction of motion of synchronous electron, is described by the longitudinal displacement s and the relative momentum deviation δ with respect to the momentum of the synchronous electron.

3.1 Physical acceptance

The physical acceptance in horizontal plane $A_{x,phys}$ is the minimum value of A_x which exists at least one location s_0 around the ring for which $x_{max}(s_0)=a_x(s_0)$ where $a_x(s_0)$ is horizontal half width of vacuum chamber at s_0. The acceptance [9] that can be sustained by the ring is

$$A_{x,\,phys}(\delta)=\min_{s_0\in[0,C]}\left[\frac{\left(a_x(s_0)-\eta(s_0)\delta\right)^2}{\beta_x(s_0)}\right]$$

where $\beta_x(s_0)$ and $\eta(s_0)$ are the beta function and dispersion function at location s_0. Physical acceptance $x_{phys}(s,\delta)$ at location S with momentum deviation δ, using the above value of $A_{x,phys}$ is given as

$$x_{phys}(s,\delta)=\pm\left(\sqrt{A_{x,\,phys}(\delta)\beta_x(s)}\right)+\eta(s)\delta$$

Using Indus-2 lattice functions β_x, η and half width of vacuum chamber $a_x = 32$ mm along the circumference C, the physical acceptance in horizontal plane for energy deviation $\delta = 0$ and $\pm1\%$ was estimated and is shown in Fig.T.3.3. The results show that the on-momentum electrons for which $\delta = 0$ are lost at maximum β_x locations whereas off-momentum electrons $\delta \neq 0$ are lost at maximum dispersion η locations.

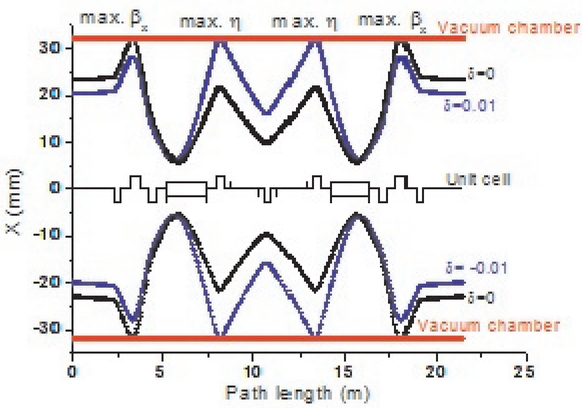

Fig.T.3.3: Physical acceptance in horizontal plane in Indus-2 for on and off energy electrons.

As there is no dispersion (or negligible small) in vertical plane, the physical acceptance $A_{z,phys}$ is the minimum value of acceptance such that there exists at least one location s_0 around the ring for which $z_{max}(s_0) = a_z(s_0)$, where $a_z(s_0)$ is vertical half width of vacuum chamber.

$$A_{z,phys} = \min_{s_0 \in [0, C]} \left[\frac{a_z^2(s_0)}{\beta_z(s_0)} \right]$$

Physical acceptance in vertical plane z_{phys} at location s, using value of $A_{z,phys}$ is given as

$$z_{phys}(s) = \pm \sqrt{A_{z,phys}\, \beta_z(s)}$$

The physical acceptance in vertical plane in Indus-2 was estimated using beta functions and uniform aperture of vacuum chamber a_z = 17 mm and is shown in Fig. T.3.4. The results show that electrons are lost in vertical plane at maximum β_z locations in the ring.

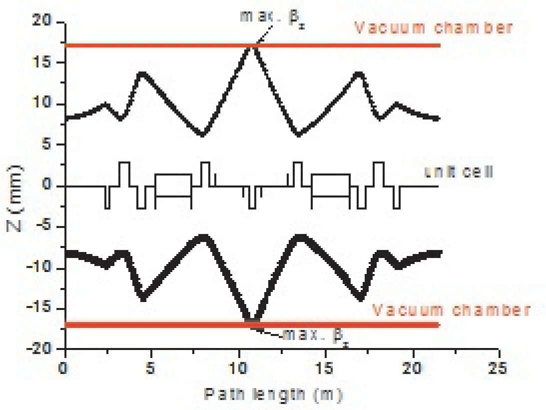

Fig. T.3.4:Physical acceptance in vertical plane in Indus-2

3.2 Dynamic aperture

The particle motion in an electron storage ring is linear if the lattice is made of perfect dipoles and quadrupoles. In a real storage ring, electrons are subjected to non-linear forces of the sextupole magnets and multipole field errors of dipoles, quadrupoles and sextupoles. With the increase in betatron amplitude, the motion of electrons become more and more non-linear due to the presence of such non-linear forces. The dynamic aperture is the smallest initial amplitude of the electron whose motion will cause its amplitude to increase until it is lost from the vacuum chamber. So the dynamic aperture is defined as the maximum stable initial transverse amplitude in the presence of nonlinearities. A proper choice of tune points helps in enhancing the dynamic aperture [4].

To find the dynamic aperture for on-momentum electrons $\delta = 0$ at the centre of long straight section in Indus-2, single particle tracking was carried out using particle tracking code RACETRACK [10]. The particle tracking was carried out up to 10,000 turns which is more than one damping time in horizontal plane τ_x (4.7 ms) at beam energy 2.5 GeV. The results of dynamic aperture in presence of both systematic and random errors using 15 different random error seeds is shown in Fig. T.3.5.

The results show that the dynamic aperture at the centre of long straight section is ~15 mm and ~6 mm in horizontal and vertical plane respectively. With these values of apertures in horizontal and vertical plane, the dynamic apertures at other locations along the circumference of ring are estimated by normalizing with β function.

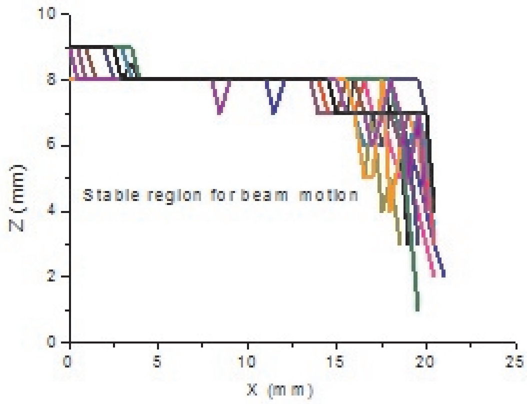

Fig. T.3.5: Dynamic aperture in Indus-2 with different random error seeds using RACETRACK

3.3 Momentum acceptance

Momentum acceptance in the horizontal plane depends on the dispersion function and it varies along the circumference of the storage ring.

An on-axis electron that suffer a large angle electron-electron scattering or inelastic scattering with residual gas atoms at the ring location S_0, its momentum deviation changes to δ_0 moves on a different closed orbit and start executing oscillation around it. Single particle tracking was carried out to find the momentum acceptance in transverse plane (ε_{trans}) using Four Dimensional (4D) and combining transverse and longitudinal planes i.e. Six Dimensional (6D) particle tracking using TRACY-3 [11] code.

The results of momentum acceptance obtained by 4D and 6D particle tracking are shown in Fig.T.3.6. The results show that the momentum acceptance in Indus-2 is limited in longitudinal plane i.e. due to RF acceptance (ε_{rf}) which is a constant parameter.

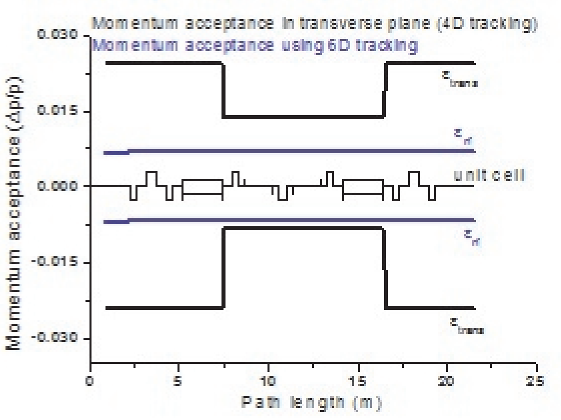

Fig. T.3.6: Momentum acceptance in Indus-2

4. Measurements of vertical and horizontal aperture

Vertical and horizontal apertures which are available for stable beam motion in Indus-2 at beam energy 2.5 GeV was measured using movable beam scrapers. Vertical and horizontal beam scrapers are installed in one of the long straight sections in the ring [12]. The experimental set-up of vertical and horizontal scraper in Indus-2 ring is shown in Fig.T.3.7. A set of experiments were performed to measure the vertical and horizontal aperture at the scrapers location at beam energy 2.5 GeV with 100 mA stored beam current.

4.1Measurement of beam lifetime with scraper movement

The beam lifetime was measured with the movement of vertical and horizontal beam scrapers independently. The experiments for the measurement of beam lifetime with scraper movement is explained below.

4.1.1 Beam lifetime with vertical scraper movement

The physical aperture available in vertical plane at the scraper location is ± 18 mm. During the normal operation, the upper blade of scraper is at +18 mm and lower blade is at -18 mm from the centre of the vacuum chamber pipe. For lifetime measurement, lower blade was moved gradually towards the beam centre using a stepper motor while upper blade was fixed at its extreme end. The experiments of beam lifetime measurement with scraper movement were carried out during beam current decay from 100 mA to 95 mA because the vacuum pressure is approximately same during the current decay time. Similar experiment was carried out with upper blade movement towards the beam centre, while lower blade position fixed at the extreme end. The measured beam lifetime at different upper blade positions with respect to the beam centre is shown in Fig. T.3.8. The results show that, during beam scraper movement up to 4.1 mm [12] from the beam centre, there is no change in beam lifetime and it remains ~13 hours. The lifetime starts decreasing, when the scraper position from beam centre becomes less than 4.1 mm. The aperture was measured by filling Indus-2 ring with beam current 100 mA uniformly in all 291 RF buckets and in another case also with one-third RF buckets kept empty. In these cases the measured aperture was found to be the same. Fig. T.3.8 show that the aperture available in vertical plane at scraper location is ±4.1 mm. When the scraper position from beam centre becomes ±0.58 mm, a sudden loss of beam takes place, which is the aperture limit for quantum lifetime and it is the minimum vertical aperture for survival of the electron beam.

Fig.T.3.7: Vertical and horizontal scrapers in the ring, 1) vertical scraper, 2) horizontal scraper,3) stepper motors for vertical and horizontal movement of scraper blades

4.1.2 Beam lifetime with horizontal scraper movement

A similar procedure was adopted to measure the beam lifetime with the horizontal scraper movement. The physical aperture available at the scraper location is ±42 mm. During the normal operation, the left blade of the scraper is at +42 mm and right blade is at -42 mm with respect to the centre of vacuum chamber pipe. For lifetime measurement left blade was moved gradually towards the beam centre using a stepper motor and the right blade was fixed at its extreme end. Similar experiment was carried out by keeping left blade fixed at its extreme and the right blade was moved. The measured beam lifetime with left scraper blade movement towards the beam centre is shown in Fig.T.3.9. The experimental results indicate that when the horizontal scraper is at ±12.45 mm from the beam centre, the beam lifetime starts decreasing before it there is no change in beam lifetime. It shows that the aperture available for beam motion in horizontal plane at the scraper location is ±12.45 mm [12]. When the scraper blade position from the beam centre becomes ±7.6 mm, very fast beam current decay takes place, which is the aperture limit for quantum lifetime and it is the minimum horizontal aperture for survival of the electron beam.

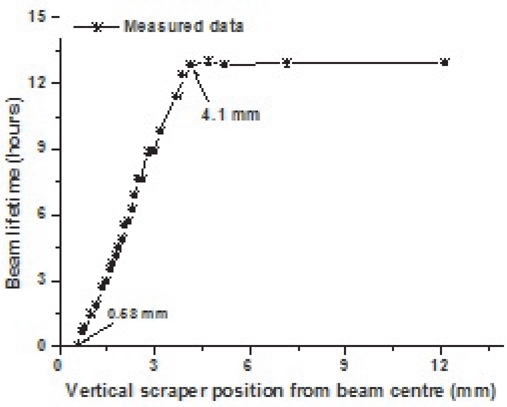

Fig.T.3.8: Beam lifetime with vertical scraper movement towards the beam centre

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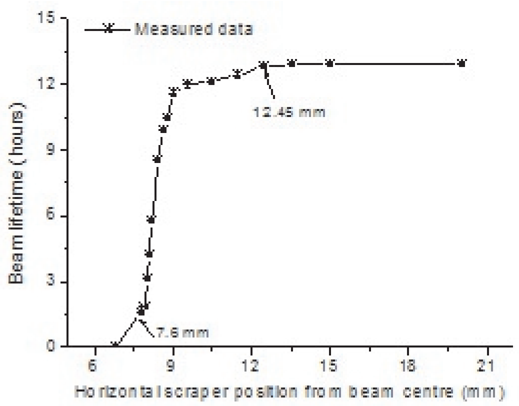

Fig.T.3.9:Beam lifetime with horizontal scraper movement towards the beam centre

5. Analysis of measured beam lifetime data

The measured beam lifetime at a particular stored beam current and beam energy is the contribution of all processes which contribute the beam losses.

The vacuum lifetime in an electron storage ring is mainly decided by elastic and inelastic scattering between the electron and the nuclei of residual gas atoms present in the vacuum chamber [6]. The beam loss rate due to elastic coulomb scattering between the electron and nuclei of residual gas atoms depends on the aperture available for beam motion and also on vacuum pressure due to presence of residual gas atoms. Beam loss rate due to inelastic scattering between the electron and nuclei of residual gas atoms depends on the vacuum pressure and limiting momentum acceptance of storage ring. At stored beam current 100 mA, 2.5 GeV vacuum pressure was measured at 32 Bayard Alpert Gauges (BAGs) which are installed in Indus-2 along the circumference of ring [13]. The gas contents in ring is also monitored by using Residual Gas Analyzers (RGAs) installed in ring. The measured gas contents at 100 mA stored current was found to be ~75% H_2 and ~25% CO. The vacuum pressure along the beam path in ring was not uniform so new expressions of shape factor due to electron-gas elastic scattering considering rectangular and elliptical shape of the vacuum chamber was derived. The shape factor for elliptical shape of vacuum chamber at scattering location j is given as [14]

$$F_j = \frac{2(\beta_x)_j\,\beta_{xm}}{a^2}\left(\tan^{-1}\left(\frac{pb}{a}\right)+\frac{pab}{a^2+p^2b^2}\right)+ \frac{2(\beta_x)_j\,\beta_x}{a^2}\left(\cot^{-1}\left(\frac{pb}{a}\right)-\frac{pab}{a^2+p^2b^2}\right)+ \frac{2(\beta_z)_j\,\beta_{zm}}{b^2}\left(\cot^{-1}\left(\frac{pb}{a}\right)+\frac{pab}{a^2+p^2b^2}\right)+ \frac{2(\beta_z)_j\,\beta_z}{b^2}\left(\tan^{-1}\left(\frac{pb}{a}\right)-\frac{pab}{a^2+p^2b^2}\right)$$

$$\text{where } p=\left(\sqrt{\frac{(\beta_x)_j\,(\beta_{xm}-\beta_x)}{(\beta_z)_j\,(\beta_{zm}-\beta_z)}}\right)$$

where β_{xm} and β_{zm} are the maximum beta functions in horizontal and vertical plane, $(\beta_x)_j$ and $(\beta_z)_j$ are beta functions at scattering location j, β_x and β_z are the beta function at maximum beta locations in vertical and horizontal plane respectively, a and b are the half aperture in horizontal and vertical plane respectively.

Using shape factor and vacuum pressure at several scattering locations along the circumference of ring, loss rate of electrons due to elastic coulomb scattering ($1/\tau_{elastic}$) is estimated as

$$\frac{1}{\tau_{elastic}} = \frac{2Z^2 r_0^2 c}{\gamma^2 kT} \langle F.P \rangle$$

where Z : atomic number of residual gas atom, r_0 :classical electron radius, γ : relativistic factor, T : absolute temperature, k: Boltzmann constant. The contribution of loss rate is more where the factor $F.P$ is high. Loss rate was estimated by averaging the value at several scattering locations. By using measured vacuum pressure obtained from BAGs, average vacuum pressure P was estimated and found to be $1.68\text{x}10^{-9}$ Torr. The estimation shows that the RF acceptance for applied total RF cavity peak voltage ~1200 kV is ~0.7% and it is the limiting momentum acceptance for stored electrons in ring. By using measured vertical and horizontal apertures and measured vacuum pressure, vacuum lifetime due to elastic gas scattering using new derived expression with 100 mA stored current at beam energy 2.5 GeV was found to be ~26.9 hours and by using average vacuum pressure and limiting momentum acceptance, vacuum lifetime due to inelastic scattering was found to be ~28.7 hours. The vacuum lifetime due to the occurrence of both the process simultaneously was ~13.9 hours.

The momentum acceptance along the beam path was estimated from 6D particle tracking using ELEGANT code [15]. With the value of momentum acceptance, bunch volume and number of electrons within a bunch at several scattering locations where the probability of electron loss is maximum, Touschek loss rate was estimated by averaging the value at all scattering locations. The Touschek lifetime which is also govern by betatron coupling, with 100 mA stored current uniformly distributed in all 291 RF buckets at beam energy 2.5 GeV using measured betatron coupling coefficient ~0.5 % [16] was found to be ~285 hours. The quantum lifetime due to the emission of synchrotron radiation is significantly higher as compared to vacuum and Touschek lifetime and thus do not influence the total beam lifetime.

Using vacuum lifetime ~13.9 hours and Touschek lifetime ~285 hours, we get beam lifetime ~13.2 hours which is close to the measured beam lifetime.

To separate the contribution of vacuum and Touschek lifetime from measured beam lifetime, experiments were conducted by storing 100 mA beam current uniformly in 291 (all RF buckets fill), 260 (~10% buckets empty), 194 (~one third buckets empty). The bunch fill pattern was observed by using Wall Current Monitor (WCM) installed in one of the long straight sections in the ring. The WCM signal shows the bunch fill pattern which is observed on a cathode ray oscilloscope. In all these experiments, vacuum pressures at all BAGs in the ring was measured and found to be similar so the vacuum lifetime at a given stored current is the same. The experiments indicate that the vacuum lifetime depends on the average stored beam current. It was also observed that the transverse beam sizes and bunch length were the same which indicate that the bunch volume were the same in these experiments. The transverse beam sizes were measured using X-ray diagnostic beam line whereas bunch length was measured using visible diagnostic beamline which are connected to the ports of one of the dipole magnets of Indus-2 ring. The Touschek lifetime is inversely proportional to number of electrons in a bunch. By assuming vacuum pressure same and linear dependence of Touschek lifetime on number of electrons in a bunch, vacuum and Touschek lifetime were separated from the measured beam lifetime. From these measurements vacuum lifetime was found to be ~13.8 hours whereas Touschek lifetime to be ~318 hours accordingly the total beam lifetime is ~13.2 hours. So these experiments validate the theoretical estimated values of vacuum and Touschek lifetime.

6. Advantages of measurements of aperture

From the measured vertical and horizontal apertures using beam scrapers it was found that the vertical aperture ~4.1 mm is less as compared to the dynamic aperture estimated using particle tracking code. The small vertical aperture affect the vacuum lifetime due to elastic scattering between electrons and nuclei of residual gas atoms. For the improvement of vertical aperture, vertical closed orbit was corrected globally in the ring. With correction of vertical closed orbit and all other parameters unchanged, the beam lifetime at 2.5 GeV, 100 mA stored current increased to ~18 hours which was ~13 hours before orbit correction. The vertical closed orbit and beam current decay before and after correction is shown in Fig.T.3.10 and T.3.11 respectively. The aperture measurement studies were also useful to decide the appropriate vertical aperture (±8 mm) of the new vacuum chamber of insertion devices to be installed in the ring without affecting beam lifetime due to elastic coulomb scattering between electrons and residual gas atoms. With vertical aperture ±8 mm of new vacuum chamber at the locations of two planar undulators U1 and U2, beam lifetime at 100 mA stored current, 2.5 GeV was measured. With same vacuum pressures restoration as before the installation of U1 and U2 and other parameters like RF cavity voltage, beam orbit in the ring, same beam lifetime was observed. So the reduction of vertical aperture at undulators location from ±17 mm to ±8 mm does not affect the beam lifetime.

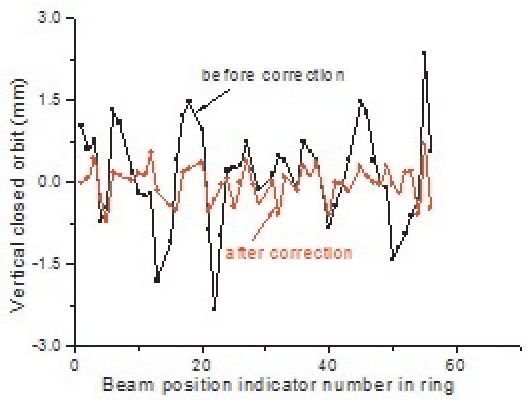

Fig. T.3.10: Vertical closed orbit before and after correction

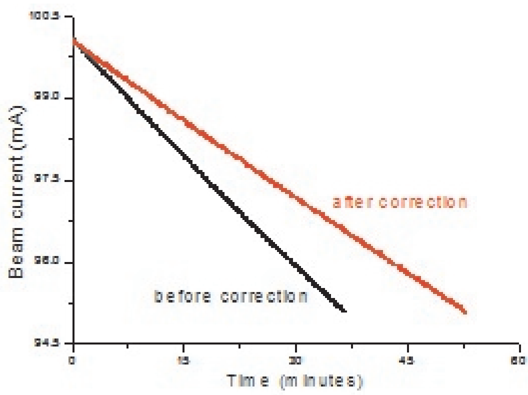

Fig. T.3.11: Beam current decay with vertical orbit correction

7. Methods for the enhancement of Touschek beam lifetime

The emittance of the present operating lattice is ~130 nm.rad and has significantly large Touschek lifetime as compared with vacuum lifetime.

In a low emittance electron storage ring operating at an average vacuum pressure 1×10^{-9} Torr, the beam lifetime is limited due to large angle intra-beam coulomb scattering i.e. electron-electron scattering within a high density electron bunch i.e. Touschek scattering. For the enhancement of Touschek lifetime, we have to increase the momentum acceptance. The momentum acceptance in transverse plane is optimized while designing the lattice and the RF acceptance is increased by increasing the RF cavity voltage. The alternative methods for the enhancement of Touschek lifetime were studied which are as follows.

7.1 Increase in vertical beam emittance

Increase in vertical beam emittance give rise in vertical beam size i.e. the increase in bunch volume which lead to increase in Touschek lifetime. By operating the storage ring near to the linear difference coupling resonance, there is an increase in vertical emittance i.e. vertical beam size that leads to an increase in Touschek lifetime.

Experiments were conducted to bring horizontal and vertical betatron tune near to the linear difference coupling resonance. For experiment, the current in one of the quadrupole (Q3D) family was increased in small steps and observed the change in horizontal and vertical tune. With the increase in Q3D current, horizontal and vertical beam sizes were observed simultaneously using X-ray diagnostic beam line. The changes in betatron tunes and beam sizes with Q3D current are shown in Fig. T.3.12(a) and T.3.12(b) respectively.

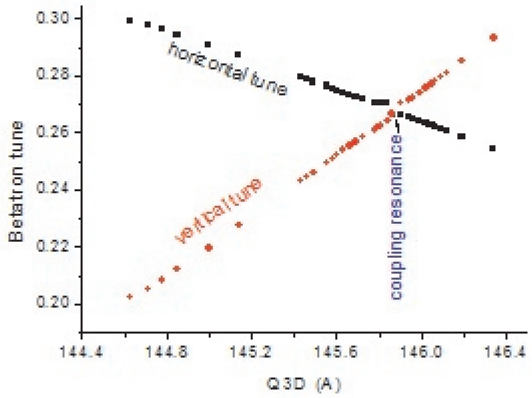

Fig. T.3.12(a): Variation in tunes with change in Q3D current

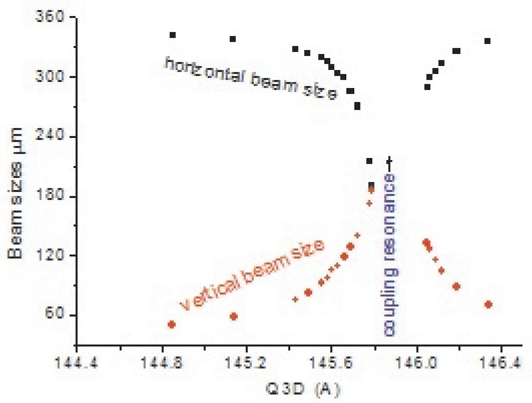

Fig. T.3.12(b): Variation in beam sizes with change in Q3D current

The measured results show that near to the coupling resonance, there is increase in vertical beam size and simultaneously decrease in horizontal beam size. No significant increase in beam lifetime at 100 mA stored current was observed which indicates that the beam lifetime at this stored beam current is not Touschek limited.

7.2 RF phase modulation

Touschek lifetime can be enhanced by decreasing the density of electron bunches stored in the ring. This can be done by applying RF phase modulation on the RF wave of signal generator. In order that the cavity field can follow any modulation in the input RF wave, the bandwidth of the cavity which is the ratio of cavity resonant frequency to the loaded quality factor should be comparable to or wider than the modulation frequency [17]. In Indus-2, cavity band width is about ~50 kHz, so the cavity can follow the phase modulation up to about this frequency with certain amplitude and phase response due to the cavity impedance.

A simulation study of the application of RF phase modulation of nearly one and two times of synchrotron oscillation frequency in main RF of Indus-2 ring at beam energy 2.5 GeV is explained below.

7.2.1 Effect of the RF phase modulation on distribution of electrons in a bunch

Particle tracking considering 5000 electrons in a bunch was carried out in longitudinal plane for 10,000 turns with modulation frequency of nearly one and two times of synchrotron frequency [18] and with different modulation amplitude. With applied RF modulation frequency of 20.5 kHz, 41 kHz and modulation amplitude of 3^o, the longitudinal phase space of electrons at the start of tracking i.e. 0^{th} and $10{,}000^{th}$ turns are shown in Fig.T.3.13(a)-(b) and T.3.14(a)-(b) respectively. The results show that by applying the RF phase modulation of nearly two times of synchrotron oscillation frequency (41 kHz), the distribution of electrons in a bunch in phase space changes. In low emittance storage ring, the density of electrons in a Gaussian bunch is higher at the centre. Due to high density of electron at the bunch centre, there is a large scattering amplitude which causes loss of electrons and decrease in beam lifetime. As seen in Fig.T.3.14(b), the density of the electrons at the centre of the bunch reduces and the distribution is divided in two parts on the application of RF phase modulation so there is less scattering. The electrons execute two states of stable oscillations, the phases of which are opposite to each other, there arises a quadrupole mode longitudinal oscillation of the electrons within the bunch and it leads to increase in bunch length (increase in bunch volume) which causes the increase in Touschek lifetime [17].

RF phase modulation with synchrotron frequency

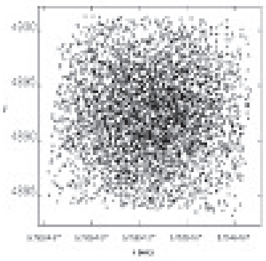

Fig.T.3.13(a): Phase space at t=0

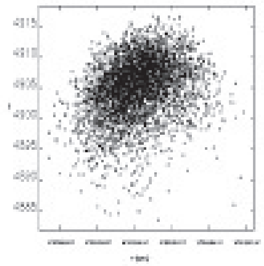

Fig.T.3.13(b): Phase space after 10,000 turns

RF phase modulation at twice of the synchrotron frequency

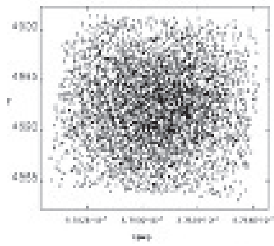

Fig.T.3.14(a): Phase space at t=0

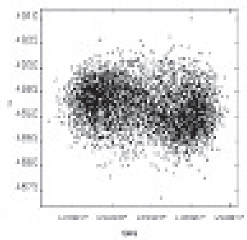

Fig.T.3.14(b): Phase space after 10,000 turns

7.2.2 RF phase modulation experiment

Experiment was performed to see the effect of RF phase modulation by applying two times of synchrotron frequency (~41 kHz) in Indus-2 ring at 2.5 GeV, 100 mA stored beam current. The beam spectrum with application of RF phase modulations is shown in Fig. T.3.15.

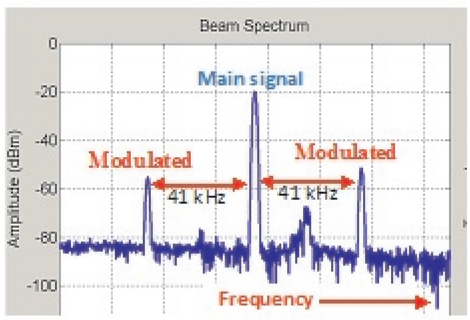

Fig. T.3.15: Beam spectrum with RF phase modulation

From the beam spectrum showing the phase modulated signal, it was observed that the beam has undergone the RF phase modulation. No significant increase in beam lifetime was observed by the application of RF phase modulation which indicate that the beam lifetime at this stored beam current is not Touschek limited in Indus-2.

8. Conclusions

Acceptances of Indus-2 ring for stable motion of electron beam in transverse and longitudinal planes has been estimated using analytical formulations and particle tracking codes. The vertical and horizontal aperture available for stable beam motion in ring has been measured using vertical and horizontal beam scrapers installed in one of the long straight sections in ring. The measurement of apertures using beam scrapers was very useful to know the beam loss contributors and for improvement in beam lifetime and also in deciding the appropriate vertical aperture (±8 mm) for the new vacuum chamber of the insertion devices for stable beam motion without affecting beam lifetime due to elastic coulomb scattering between electrons and residual gas atoms. By using measured aperture, measured vacuum pressure and applied RF cavity gap voltage, the contribution of vacuum and Touschek lifetime was estimated. The estimated value of vacuum and Touschek lifetime was verified by storing beam current uniformly in all RF buckets and storing same total amount of beam current by keeping some RF buckets empty. The methods for the enhancement of Touschek lifetime was also studied.

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