CLS Beam Lifetime and Stability Studies

5.2.69.3 Rev. 0
(formerly 2.1.19C)

Date: 1999-Nov-24

Canadian Light Source
107 North Road
University of Saskatchewan
Saskatoon, Saskatchewan Canada

	Signature	Date
	Original on File – Signed by	
Author	(R.M. Silzer)	
Reviewer #1	(J.C. Bergstrom)	
Reviewer #2	(L.O. Dallin)	
Approver	(M. de Jong)	

REVISION HISTORY

Revision	Date	Description	Author
B	1999-Jul	Original issue	R.M. Silzer
C	1999-Nov-24	Updated RF frequency to 500 MHz	R.M. Silzer

Saskatchewan Accelerator Laboratory
University of Saskatchewan
Saskatoon SK S7N 5C6 Canada

date: **CLS Beam Lifetime Studies**

date: **November 22 1999**

from: **R. Mark Silzer**

reference: 2.1.19.C

ABSTRACT

This report outlines the beam stability analysis and beam lifetime for the CLS lattice. The analysis was accomplished using the program ZAP, and was preformed on the CLS lattice.

Beam lifetime and stability is a major consideration in the design of the CLS lattice. Users will require a stable beam with a lifetime that allows for infrequent fillings of the storage ring. The beam lifetimes are a function of such things as the lattice parameters, RF voltage, vacuum chamber geometry and composition, beam energy, and vacuum. In general, the beam lifetime is limited by Touschek scattering, bremsstrahlung and elastic scattering, and quantum lifetime. Bremsstrahlung and elastic scattering are both a function of the residual gas pressure and composition in the vacuum chamber, and are often grouped together as the gas scattering lifetime.

In the CLS storage ring, beam lifetime is limited by the gas scattering lifetime and the Touschek lifetime. These two affects are both highly affected by the energy of the electron beam. Touschek scattering (intrabeam coulomb scattering) lifetime scales roughly as the energy cubed while the elastic scattering lifetime scales like the energy squared. Thus, beam lifetime is destined to be inherently worse at the lower operating energies of the machine. Other operation choices that greatly affect the beam lifetime include the operating gap of insertion devices and the transverse coupling of the electron beam. The largest effects in the gap size are due to elastic scattering which decreases as the square of the operating gap. Touschek lifetime is a function of the charge density in the beam, so is decreased by running at smaller coupling which decreases the vertical beam size. Touschek lifetime is also decreased by reduced gap sizes. As the aperture decreases this may decrease the energy acceptance of the lattice imposed by the aperture limits. With this in mind, the lifetime analysis was investigated at different values of beam energy, gap sizes, horizontal coupling, and energy loss to simulate possible modes of running of the CLS.

THE INPUT PARAMETERS:

The inputs for the program ZAP include the beam parameters, lattice parameters, the RF parameters, and the characteristics of the vacuum chamber. The lattice parameters are supplied by the program Dimad. The beam parameters are given from Dimad and some subroutines contained in the ZAP program. The RF cavity characteristics are taken from a 1996 EPAC paper called, “Updated Impedance Estimates of the PEP-II RF Cavity”, page 2035. This gives us a representative higher order mode spectrum for a well damped RF cavity. The values were scaled to 500 MHz. Machine parameters and given in Table 1 and beam parameters are given in Table 2.

Table 1: Energy Independent Machine Parameters

Ring Circumference	170.880 m
Momentum Compaction normal operation	 0.0038016
Tune ν_x ν_y	 10.22 3.26
βx_{ave} βy_{ave} βx (in the long straights) βy (in the long straights)	6.0 m 11.0 m 9.32 m to 8.53 m in the center 6.08 m to 4.62 m in the center
RF Cavity Frequency Harmonic number Voltage Cavity equivalent broadband impedance	 500 MHz 285 variable 0.5 Ω/cell
Vacuum Equivalent vacuum radius Cavity radius material Gas Pressure Residual gas	 20 mm 50 mm stainless steel 133.3 nPa (1.0 ntorr) diatomic Nitrogen equivalent
Number of bunches filled out of 285	204

Extensive impedance modeling of their elliptical vacuum chamber was done at SPEAR3. For their vacuum chamber with major and minor axes of 43.3 mm and 18.4 mm respectively, an effective radius of 23 mm was calculated. Our vacuum chamber is currently 31 mm by 16 mm. This led to the value of 20 mm being used for the effective radius of the vacuum chamber (see Table 1).

Table 2: Energy Dependent Beam Parameters

Energy	1.5 GeV
Natural Damped Emittance, ε_x	4.85 nm-rad
Natural Energy Spread, δ	5.72e-4
Energy Loss/Turn	0.0627 Mev/Turn
Damping Times	
τ_x	17.2 msec
τ_y	27.3 msec
τ_E	19.3 msec
Energy	2.0 GeV
Natural Damped Emittance, ε_x	8.623 nm-rad
Natural Energy Spread, δ	7.63e-4
Energy Loss/Turn	0.1982 Mev/Turn
Damping Times	
τ_x	7.25 msec
τ_y	11.5 msec
τ_E	8.15 msec
Energy	2.5 GeV
Natural Damped Emittance, ε_x	13.47 nm-rad
Natural Energy Spread, δ	9.54e-4
Energy Loss/Turn	0.484 Mev/Turn
Damping Times	
τ_x	3.71 msec
τ_y	5.89 msec
τ_E	4.17 msec
Energy	2.9 GeV
Natural Damped Emittance, ε_x	18.13 nm-rad
Natural Energy Spread, δ	1.106e-3
Energy Loss/Turn	0.876 MeV/Turn
Damping Times	
τ_x	2.38 msec
τ_y	3.77 msec
τ_E	2.67 msec

Option 1 of ZAP calculates the single bunch current thresholds. These effects are driven by the low Q broadband impedances of the ring. The most pronounced longitudinal instability is the microwave instability (also called turbulent bunch lengthening). Above a threshold current, the bunch length will increase turbulently. Two major transverse single bunch thresholds are of interest, transverse fast blowup and the transverse mode coupling stability (also known as the fast head-tail instability).

The lattice was investigated at 1.5 GeV and 2.9 GeV for RF voltages ranging from 1.5 MV to 4.0 MV and found to be dominated by the longitudinal current thresholds. The lattice was also investigated with increased values for energy loss to simulate the addition of insertion devices to the lattice. This resulted in only minor affects to the results.

At 2.9 GeV the single bunch threshold average current limit varied from a low at 1.5 MV of 2.9 A to 3.6 A for RF voltages in excess of 3.1 MV. The average current is based on filling of 204 buckets out of a possible 285. At 1.5 GeV the single bunch thresholds are lower, ranging from 720 mA at 1.5 MV to less than 500 mA at gap voltages in excess of 3.1 MV.

Option 2 of ZAP is used to determine the longitudinal bunch parameters of the electron beam in the storage ring. This information is subsequently used in option 7 which calculates emittance and bunch length growth from intrabeam scattering. These values are also used for beam lifetime calculations. The higher energy loss values were used to simulate the addition of insertion devices. Transverse coupling values of 1% and 10% were used and found to give no change in the bunch length results but showed differences in the equilibrium emittance values. No change in the beam energy spread was observed for any of the studied cases. The results for an RF voltage of 2.4 MVare given in Table 3.

:

Table 3: CLS Longitudinal Bunch Parameters

Energy (GeV)	Coupling (%)	E_{loss} (MeV/Turn)	Average Current (A)	Equilibrium Emittance (nm-rad)	Bunch length (cm)
1.5	1	0.0627	200	5.26	0.348
	1		500	5.785	0.336
	10		200	4.948	0.348
	10		500	5.096	0.336
	1	0.08	200	5.26	0.348
	1		500	5.785	0.336
	10		200	4.948	0.348
	10		500	5.096	0.336
2.0	1	0.1982	200	8.646	0.540
	1		500	8.682	0.526
	10		200	8.630	0.540
	10		500	8.636	0.526
	1	0.25	200	8.646	0.540
	1		500	8.682	0.526
	10		200	8.630	0.540

Table 3: CLS Longitudinal Bunch Parameters

Energy (GeV)	Coupling (%)	E_{loss} (MeV/Turn)	Average Current (A)	Equilibrium Emittance (nm-rad)	Bunch length (cm)
	10		500	8.636	0.526
2.5	1	0.4838	200	13.47	0.767
	1		500	13.48	0.755
	10		200	13.47	0.767
	10		500	13.47	0.755
	1	0.61	200	13.47	0.772
	1		500	13.48	0.760
	10		200	13.47	0.772
	10		500	13.47	0.760
2.9	1	0.876	200	18.13	0.987
	1		500	18.13	0.978
	10		200	18.13	1.010
	10		500	18.13	1.002
	1	1.1	200	18.13	0.987
	1		500	18.13	0.978
	10		200	18.13	1.010
	10		500	18.13	1.002

When calculating the gas scattering lifetimes of the storage ring one must input a parameter known as the limiting betatron acceptance. This value is the square of the physical half aperture divided by the corresponding beta function.

$$\beta\mathrm{tron}_{\mathrm{accept}} = \frac{b_{x,y}^2}{\beta_{x,y}}$$

For the bare lattice, the limiting betatron acceptance is located in the dipoles which have a half aperture of 16 mm.

$$\beta\mathrm{tron}_{\mathrm{accept}} = \frac{0.016^2}{26.97} = 9.49\mathrm{x}10^{-6}$$

With the addition of insertion devices that limit the gap height in the long straight sections, these straights will eventually define the machine's betatron acceptance limit. This limit is reached at a full gap height of about 13 mm assuming a $\beta_{y,max}$ at the insertion device of 4.8m. For a 8 mm gap insertion device the betatron acceptance is reduced to 3.333×10^{-6}. At a 5 mm gap and 4 mm gap the value is 1.30×10^{-6} and 8.33×10^{-7} respectively. As an estimate, the average ring beta function was conservatively input as 11.0 m corresponding to the average value of the vertical beta functions. Gas scattering calculations were done for energies ranging from 1.5 GeV to 2.9 GeV with energy acceptance values corresponding to an RF gap voltage of 2.4 MV. The energy acceptance was calculated (see Table 4) for the four different operating energies assuming a reasonable increase in the energy loss due to the addition of insertion devices. A residual gas pressure of 133.3 nPa (1 ntorr) of diatomic nitrogen was assumed. The gas scattering lifetime results can be seen in Table 5. Inserting a low beta section (β_y ~ 1 m) in the straights where small gap insertion devices will be installed can greatly enhance the gas scattering lifetimes.

Table 4: Energy Acceptances of CLS lattice

Energy (GeV)	Energy Loss (MeV/turn)	Energy Acceptance (%)
1.5	0.0627	3.00
	0.08	2.98
2.0	0.1982	2.48
	0.25	2.43
2.5	0.4838	1.99
	0.61	1.89
2.9	0.876	1.54
	1.1	1.37

Table 5: Gas Scattering Lifetime

Insertion Devices	Energy (GeV)	Gas Scattering Half-life
bare lattice	1.5	11.64
	2.0	17.13
	2.5	21.49
	2.9	23.71
8mm full gap ID's	1.5	4.81
	2.0	7.87
	2.5	11.02
	2.9	13.23

Table 5: Gas Scattering Lifetime

Insertion Devices	Energy (GeV)	Gas Scattering Half-life
5mm full gap ID's	1.5	1.99
	2.0	3.42
	2.5	5.09
	2.9	6.49
4 mm full gap ID's	1.5	1.30
	2.0	2.25
	2.5	3.41
	2.9	4.42

In the Touschek scattering calculation the individual lifetimes are calculated point-by-point throughout the lattice and a weighted average is taken. In this calculation, the momentum acceptance is required at every point in the lattice. What is taken for this value is the minimum value of the RF acceptance, the physical aperture or the dynamic aperture. For the bare lattice, a physical half aperture of 20 mm was used throughout the lattice. The dynamic aperture of the lattice is roughly 20 mm out to near the energy acceptance and is not the limiting factor in our case. The energy acceptance given in Table 4 tends to dominate the Touschek lifetime calculations.

It is clear from the results shown below that the Touschek lifetime is very limited at the lower running energy of 1.5 GeV. This will invariably affect the running mode of the machine at this energy. Lower currents and higher coupling are needed to achieve better beam lifetimes.

There are a few things that should be noted concerning different RF voltages. Touschek lifetimes increase with increasing RF voltage due to the increase in the energy acceptance in the ring. There is a limit to the gain in lifetime from increasing the RF voltage. If the voltage is increased too much this tends to shorten the bunch lengths and increases the charge density, resulting in a slight decrease in the lifetimes. Touschek lifetime results are given in Table 6 for 2.4 MV.

Table 6: Touschek Lifetime for 2.4 MV RF

Energy (GeV)	Average Beam Current (mA)	Energy Loss (MeV/turn)	Coupling (%)	Touschek half-life (hrs)
BARE LATTICE				
1.5	200	0.0627	1	10.65
			10	32.32
	500		1	10.65
			10	4.39

Table 6: Touschek Lifetime for 2.4 MV RF

Energy (GeV)	Average Beam Current (mA)	Energy Loss (MeV/turn)	Coupling (%)	Touschek half-life (hrs)
2.0	200	0.1982	1	28.47
			10	89.88
	500		1	11.13
			10	35.08
2.5	200	0.4838	1	60.32
			10	190.76
	500		1	23.77
			10	75.11
2.9	200	0.876	1	85.55
			10	270.52
	500		1	23.77
			10	107.22
WITH ID’s				
1.5	200	0.08	1	10.52
			10	31.93
	500		1	4.34
			10	12.57
2.0	200	0.25	1	26.84
			10	84.74
	500		1	10.50
			10	33.04
2.5	200	0.61	1	53.07
			10	167.81
	500		1	20.91
			10	66.08
2.9	200	1.1	1	64.38

Table 6: Touschek Lifetime for 2.4 MV RF

Energy (GeV)	Average Beam Current (mA)	Energy Loss (MeV/turn)	Coupling (%)	Touschek half-life (hrs)
			10	203.57
	500		1	25.55
			10	80.78

The total beam lifetime (half-life) can be calculated for combined gas scattering and Touschek scattering.

$$1/\mathrm{Ttot} = 1/\mathrm{Tgas} + 1/\mathrm{Ttous}$$

For example, for the bare lattice at 2.9 GeV with 500 mA of beam running with 10% coupling and 1.6 MV RF gives:

$$\mathrm{Ttot} = \frac{1}{1/(22.06\mathrm{hrs}) + 1/(45.09\mathrm{hrs})} = 14.81\mathrm{hrs}$$

Total lifetime results are given in Table 7.

Table 7: Total Half-Life

Insertion Devices	Energy (GeV)	Gas Scattering Half-life	Touschek Half-life 1% coupling	Touschek Half-life 10% coupling	Total Half-life 1% coupling	Total Half-life 10% coupling
bare lattice	1.5	11.64	4.39	12.73	3.19	6.08
	2.0	17.13	11.13	35.04	6.75	11.51
	2.5	21.49	23.77	75.11	11.29	16.71
	2.9	23.71	33.91	107.22	13.95	19.42
8mm full gap ID’s	1.5	4.81	4.34	12.57	2.28	3.48
	2.0	7.87	10.50	33.04	4.50	6.36
	2.5	11.02	20.91	66.08	7.22	9.44
	2.9	13.23	25.55	80.78	8.72	11.37
5mm full gap ID’s	1.5	1.99	4.34	12.57	1.36	1.72
	2.0	3.42	10.50	33.04	2.58	3.10

Table 7: Total Half-Life

Insertion Devices	Energy (GeV)	Gas Scattering Half-life	Touschek Half-life 1% coupling	Touschek Half-life 10% coupling	Total Half-life 1% coupling	Total Half-life 10% coupling
	2.5	5.09	20.91	66.08	4.09	4.73
	2.9	6.49	25.55	80.78	5.18	6.01
4 mm full gap ID's	1.5	1.30	4.34	12.57	1.00	1.18
	2.0	2.25	10.50	33.04	1.85	2.11
	2.5	3.41	20.91	66.08	2.93	3.24
	2.9	4.42	25.55	80.78	3.77	4.19

The above table was computed for 500 mA (204 of 285 buckets filled), 2.4 MV RF, and 1 nTorr residual gas pressure of diatomic nitrogen.

It should be noted that the extended Touschek lifetime was not calculated. If an electron is scattered in a dispersive region, it will induce a horizontal betatron oscillation on the beam. Skew components in the lattice can couple the horizontal motion into a vertical motion that may exceed the vertical aperture of the machine. This is known as the extended Touschek lifetime. There exists a modified version of ZAP that takes into account the extended Touschek lifetime. This will be studied at a later date. Very roughly one can expect about a 5 to 30% decrease in the Touschek lifetimes when smaller gap insertion devices are introduced at 1% lattice coupling. (5% for larger ID gaps and 30% for the smallest ID gaps) At 10% lattice coupling, the percentage decreases in lifetimes will be greater.

The bare lattice is dominated by gas scattering lifetime at 2.9 GeV. At 1.5 GeV, the bare lattice has more comparable Touschek and gas scattering lifetimes. As insertion devices are added, gas scattering becomes more of a limiting factor. Referring to Table 7 it can be seen that operation at 1.5 GeV or even 2.0 GeV may be impractical if any smaller gap devices are employed in the ring.

Longitudinal growth rates due to coupled-bunch instabilities were also examined. For this analysis, the longitudinal higher order modes from the PEP-II cavity were used. A gap voltage of 800kV/cavity was used for three cavities. The Zotter formalism for coupled-bunch instabilities was used which yielded more pessimistic results than the Wang formalism. The shunt impedances were enhanced by the number of cavities to simulate a pessimistic case. The ZAP code sorts the growth rate for different instabilities and those faster than the damping time will need to be suppressed. The longitudinal damping times for the lattice are 19.3 ms and 2.67 ms for 1.5 GeV and 2.9 GeV operation respectively. Operating at the lower energy and higher currents requires more damping. At 250 mA, longitudinal damping should not be required at 2.9 GeV. At 200 mA damping will be required at energies below 2.7 GeV. Once we hit 1.5 GeV, damping will be a necessity at currents higher than about 25 mA.

For comparison, the longitudinal growth rates were also studied using a superconducting cavity similar to the one used at CESR in Cornell. For this analysis, a two-times shunt impedance enhancement was used along with the worst 20 modes of the calculated longitudinal HOM spectrum. Damping will be required for energies below about 1.7 GeV for 500 mA of current. No damping will be required for energies above 2.1 GeV for currents up to 1 A.