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# EXPERIENCE WITH A HIGH-BRIGHTNESS STORAGE RING: THE NSLS 750 MeV VUV RING

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The NSLS VUV ring is the first implementation of the proposals of R. Chasman and G. K. Green for a synchrotron radiation source with enhanced brightness: Its lattice is a series of achromatic bends with two zero-gradient dipoles each, giving small damped emittance; and these bends are connected by straight sections with zero dispersion to accomodate wigglers and undulators without degrading the radiation damping properties of the ring.[1] The virtues of the Chasman-Green lattice, its small betatron and synchrotron emittances, may be understood with some generality;[2] e.g. the electron $\gamma m_0 c^2$ energy and the number of achromatic bends M sets a lower limit on the betatron emittance of

$$\varepsilon_x > 7.7 \times 10^{-13} \quad \gamma^2/M \text{ meter-radians}$$

There is strong interest in extrapolation of this type of lattice to 6 GeV and to 32 achromatic bends. The subject of this report is the progress toward achieving performance in the VUV ring limited by the radiation damping parameters optimized in its design.[3]

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The VUV ring characteristics are listed in Table I. The operating energy has been raised from the original design specification of 700 MeV to 750 MeV, to provide somewhat harder radiation for an X-ray lithography experiment. At present, one of the two available dispersionless straight sections contains a rare-earth cobalt undulator[4] with 38 periods, 65 mm each. Its gap is varied to provide K values to 2.4. With the VUV ring operating at 250 MeV, this magnet supplies 3500 Å light for the Brookhaven free electron laser experiment.[5] Recently, the undulator has also been providing 500 - 1000 Å radiation to other experimentors during 750 MeV operation. The remaining insertion will accommodate an undulator for a transverse optical klystron experiment.[6] At present, the ring performance may be summarized as follows:

The maximum current stored in the VUV ring during the 750 MeV operation is 400 milliamperes in one bunch and 385 mA in three equally spaced bunches. In either case, the horizontal emittance is $1.7 \times 10^{-7}$ meter-radians, and is practically independent of current. This is consistent with the emittance expected from quantum fluctuations in the synchrotron radiation. The vertical emittance is usually about $1.2 \times 10^{-9}$ meter-radians. It is weakly dependent on current and on the number of bunches. Ion trapping is believed to be the cause of the current dependence of the vertical emittance and the current dependent vertical tune spread observed with three bunches stored. Beam lifetime is consistent with the expected loss rate from Touschek scattering and scattering from the residual gas. Multibunch longitudinal instability appeared at 2 mA, and has been controlled by damping of parasitic modes and by feedback. The highest peak current observed to date is 62 amperes. The bunch length increase linearly with current, and reaches 980 picoseconds FWHM with 400 mA in one bunch. The following is a list of phenomena associated with the performance limits of the ring.

## COUPLED BUNCH INSTABILITY

The first coherent instability observed was coupled-bunch synchrotron oscillations driven by parasitic modes in the RF cavity. The expected and observed threshold of the instability was 2 mA.[7,8] It was still possible to store 200 mA; the synchrotron oscillations at this current reached a limit of 0.75 nsec. Damping antennae, designed by Norman Fewell,[9] have been installed in the RF cavity, and the instability threshold is now 20 - 40 mA, depending on cavity tuner position. The antennae couple to electric fields in the cavity, and are located in regions of relatively small electric fields for the accelerating mode. The antennae are matched to 50 ohms and further decoupled from the fundamental mode by water cooled shorted-stub filters. The antennae reduce the impedance of the most important higher modes by 15 - 40 dB, while neglegibly reducing the Q of the fundamental.

The threshold is moved beyond 385 mA in three bunches by a feedback system. The detectors of this system were designed and tested in prototype by F. Pederson, and are similar to those used in the CERN PS booster.[10] An alternative to this method for controlling coupled bunch instability, a tune splitter cavity, has been installed in the ring. It will be driven to 2.8 kilovolts at 235 MHz, the fortieth harmonic of the rotation frequency. This cavity has a shunt impedance of 2000 ohms, an unloaded Q of 40 and a resonant frequency midway between the fortieth and forty-first rotation harmonic. The shunt impedance and resonant frequency were chosen to insure cancellation of the contribution of this cavity to the risetime of all coupled bunch modes.

The current limit of 385 mA in three bunches is believed to be set by a vertical betatron instability driven by a deflecting mode in the RF cavity. This 506 MHz mode is one of the few resonances damped less than 20 dB; modifications of the cavity temperature control should shift the center frequency of this mode away from the betatron sideband.

## BUNCH LENGTH, DEPRESSION OF THE SYNCHROTRON TUNE

Bunch length measurements were done at 750 MeV for stored currents up to 380 mA in one bunch, using a Hamamatsu photodiode and a stripline monitor. The highest peak current observed was 62 amperes. Figure (1) shows bunch length versus current. The data is better approximated by a straight line than by $I^{1/3}$ dependence. Observations of the noise in the synchrotron sidebands show that, as the beam current is increased, the narrow synchrotron line broadens dramatically and its maximum, though poorly defined, shifts downward in frequency. This is demonstrated in Fig. (2). If the shifted synchrotron tune is interpreted as the incoherent synchrotron tune, and the bunch length data is reasonably well fit by turbulent bunch lengthening with a ring impedance $Z/n = 0.7$ ohms. A more reliable characterization of the ring impedance will be possible when data on energy spread an bunch length at several energies has been collected.

The 400 mA current limit with one bunch is consistent with the usual injection rate and the high Touschek scattering rate. At present, no coherent instability is clearly associated with this limit.

## BEAM LIFETIME

An effort has been made to separate the effects of Touschek scattering and residual gas scattering at 750 MeV. Both processes produce a fractional beam loss rate d(ln I)/dt which has a linear dependence on average ring current, due to the current dependence of the gas pressure in the ring. The fractional Touschek loss rate is distinguished by its linear dependence on the inverse of the volume occupied by the beam. This volume was varied by changing the number of stored bunches and by changing the linear coupling with skew quadrupoles. With 1.8 mA in one bunch, the lifetime is 1200 minutes with the vertical beam size $\sigma y = 0.22$ mm and 1040 minutes for $\sigma y = 0.12$ mm. If the difference in lifetime is due to Touschek scattering, the residual gas scattering lifetime at this current would be 1470 minutes. Based on gas composition measurements of Mathewson[11] and the gas scattering calculation of Pellegrini,[12] we infer a pressure of 0.85 nanotorr at this current. Fig. (3) shows the dependence of beam loss rate on current for one or three stored bunches. With one bunch stored and skew quadrupole settings optimized, the vertical beam size was $0.12 \text{ mm} \leq \sigma_y \leq 0.14$ mm, corresponding to $1.0 \times 10^{-9} < \varepsilon_y < 1.4 \times 10^{-9}$ meter-radians. With three bunches stored, $0.13 \text{ mm} < \sigma_y < 0.19$ mm, corresponding to $1.2 \times 10^{-9} < \varepsilon_y < 2.5 \times 10^{-9}$ meterradians. In both cases, $\varepsilon_x = 1.7 \times 10^{-7}$ meter-radians. The physical aperture of the ring was set by the 28 mm full gap of the FEL undulator during these measurements. The lowest curve is the result of extrapolating the loss rate to an infinite number of bunches; this should give the loss rate due to residual gas scattering. Evidently, gas scattering contributes about 30% of the beam loss rate with three bunches. The calculated Touschek loss rate for the worst case, one bunch with $\sigma y = .13$ mm, is also shown. This plus the gas scattering curve agree with the measured lifetime within 20%.[13]

Beam lifetime occasionally changes abruptly from several hours to five minutes during operations. This has begun at any current above 100 mA and is always associated with an increase in the vertical beam size by a factor of two or three. In many cases this reduction in lifetime is accompanied by an increase in vertical tune spread. Also it is often preceded by the opening of an experimental beamline, and a change in ring pressure too small by orders of magnitude to account for the beam loss. The lifetime can be restored to normal by exciting a large amplitude betatron oscillation in the beam. Otherwise, the beam continues to decay to zero current. These symptoms could be explained by trapping of heavy ions in the beam. The worst vertical tune spread observed, $\delta\nu_y = 0.03$ FWHM, would require a density of single-charged ions of about 8 nanotorr. Assuming the same composition as the residual gas, the beam loss would be increased by $d(\ln I)/dt = 1/(160$ minutes). Heavier ions would be preferentially trapped, so the effect on lifetime could be worse.

An alternative explanation for the abrupt change to short lifetime has been put forth by A. Maschke.[14] He suggests that a speck of solid material (e.g. a 10 micron particle of titanium) would, while falling through the beam, accumulate a large enough charge to be confined within the beam. The speck would melt in about 10 milliseconds and expand or fragment. Thus the smaller fragments could be levitated even as the beam current decreases.

## 250 MeV OPERATION

For the free electron laser experiment, the undulator is closed to 21 mm full vertical aperture and injection takes place at 750 MeV. Currents up to 200 mA with 120 minute lifetime have been obtained without effort. The expected lifetime at 250 MeV is 30 minutes. However, during rampdown, vertical beam growth and precipitous loss of current take place below 400 MeV, with a lifetime as short as 5 minutes. This short lifetime does not improve even with only 10 - 20 microamps remaining. By contrast, with the undulator open, 60 mA and a 30 minute lifetime were easily achieved. The vertical beam blow-up may be cured by continous excitation of horizontal betatron oscillations, improving the lifetime to 15 minutes. This ion trapping is believed to be partially responsible for the anomalous loss rate; However, it seems unlikely that ion trapping should be important with only a few microamps stored.

The FEL undulator is at present removed from the ring for mechanical repairs. Before re-installation, extra pumps will be added to the magnet vacuum vessel. The magnet field will be measured again to search for possible causes for the short lifetime phenomenon.

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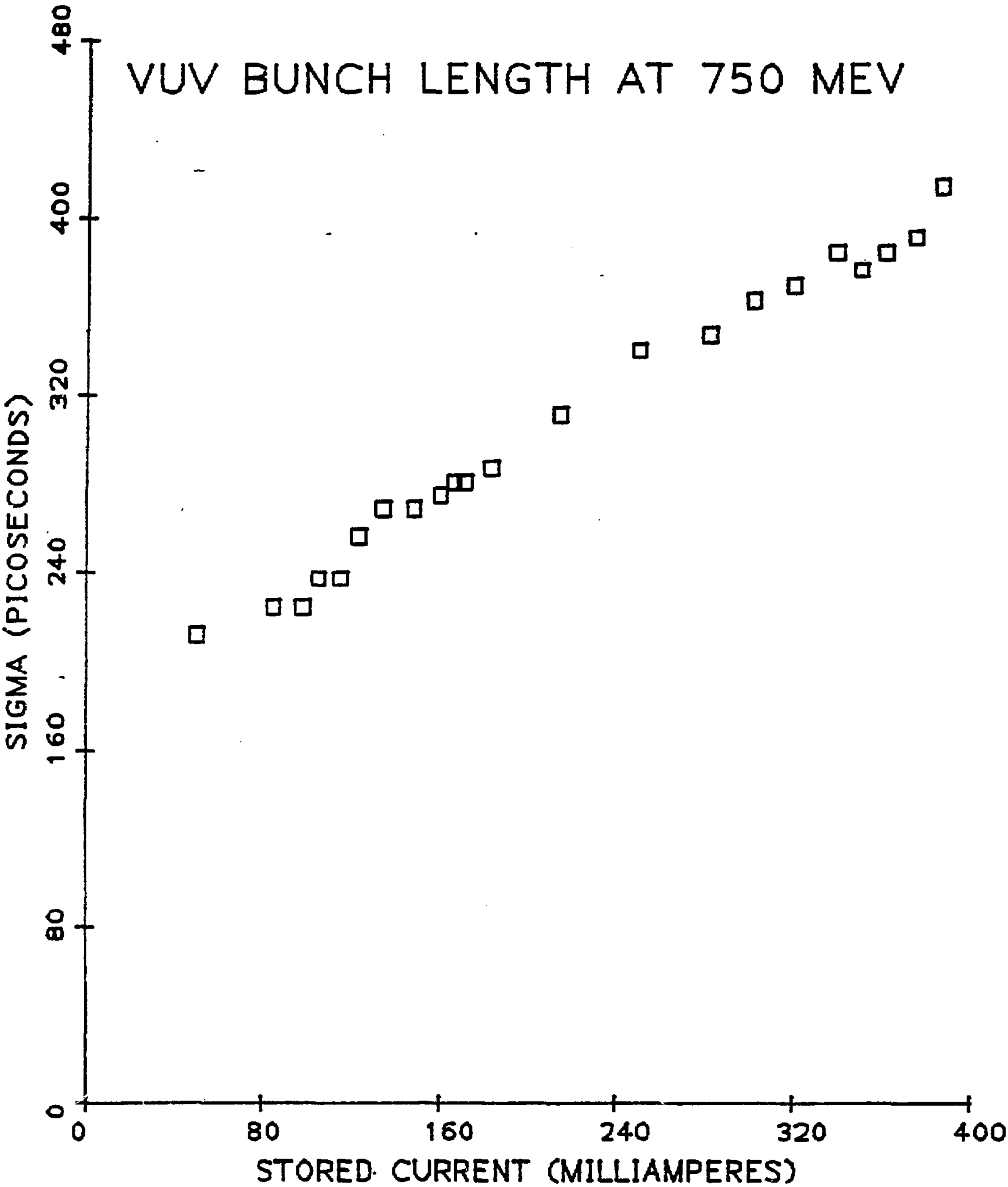
Table 1
VUV Storage Ring Parameters

| | |
|---|---|
| Energy | 0.75 Gev |
| Design current | 1 A (1.06 $10^{12}$ $e^-$) |
| $\lambda_c$ ($\varepsilon_c$) | 31.6 Å (390 eV) |
| B(ρ) | 1.3 T (1.91 m) |
| Circumference | 51.02 m |
| $\tau_{orb}$ (h) | 170.2 nsec (9) |
| Damping times | $\tau_x \approx \tau_y \approx 17$ msec; $\tau_\varepsilon \approx 9$ msec |
| Lattice structure | Separated function, doublets |
| Number of superperiods | 4 |
| Long straights | 3.26 m |
| Magnet complement | 8 B (1.5 m)<br>24 Q (0.3 m)<br>12 S (0.20 m) |
| Betatron tunes: $\upsilon_x$, $\upsilon_y$ | 3.12; 1.17 |
| βs in long straights | 11.6; 7.6 m |
| $\beta_x$, $\beta_y$ in dipole (center) | 1.5; 14.0 m |
| Maximum $\beta_x$, $\beta_y$ values | 11.9; 15.0 m |
| Maximum $X_p$ value | 1.5 m |
| Momentum compaction | 0.023 |
| Horizontal damped emittance (750 MeV) | 1.7 x $10^{-7}$ mrad |
| Energy loss per turn | 14.7 KeV |
| Frequency | 52.88 MHz |
| Harmonic number | 9 |
| Number of cavities | 1 |
| Shunt impedance/unit | ≈ 1MΩ |
| Cavity Q | ≈ 10,000 |
| Power source (tetrode) | 50 kW |
| Effective peak cavity voltage | 100 kV |
| Synchrotron oscillation frequency | 12.8 KHz |
| $\upsilon_s$ | 2.2 $10^{-3}$ |
| Natural bunch length (2σ) | 0.26 nsec |

Table 2
VUV Ring Performance

| | |
|---|---|
| Energy | 750 MeV |
| Typical charging current | 300 mA |
| Maximum current (single bunch) | 400 mA |
| Lifetime at 1 mA, one bunch | 1200 minutes |
| Lifetime at 200 mA, three bunches | 85 minutes |
| Horizontal beam emittance | 1.7 x $10^{-7}$ meter-radian |
| Vertical beam emittance (single bunch, I < 150 mA) | 1 x $10^{-9}$ mrad meter-radians |
| Vertical beam emittance (three bunches, I < 380 mA) | $\varepsilon_y$ < 2.5 x $10^{-9}$ meter-radians |



VUV BUNCH LENGTH AT 750 MEV
SIGMA (PICOSECONDS)
0
80
160
240
320
400
480
STORED CURRENT (MILLIAMPERES)
0
80
160
240
320
400


FIGURE 1

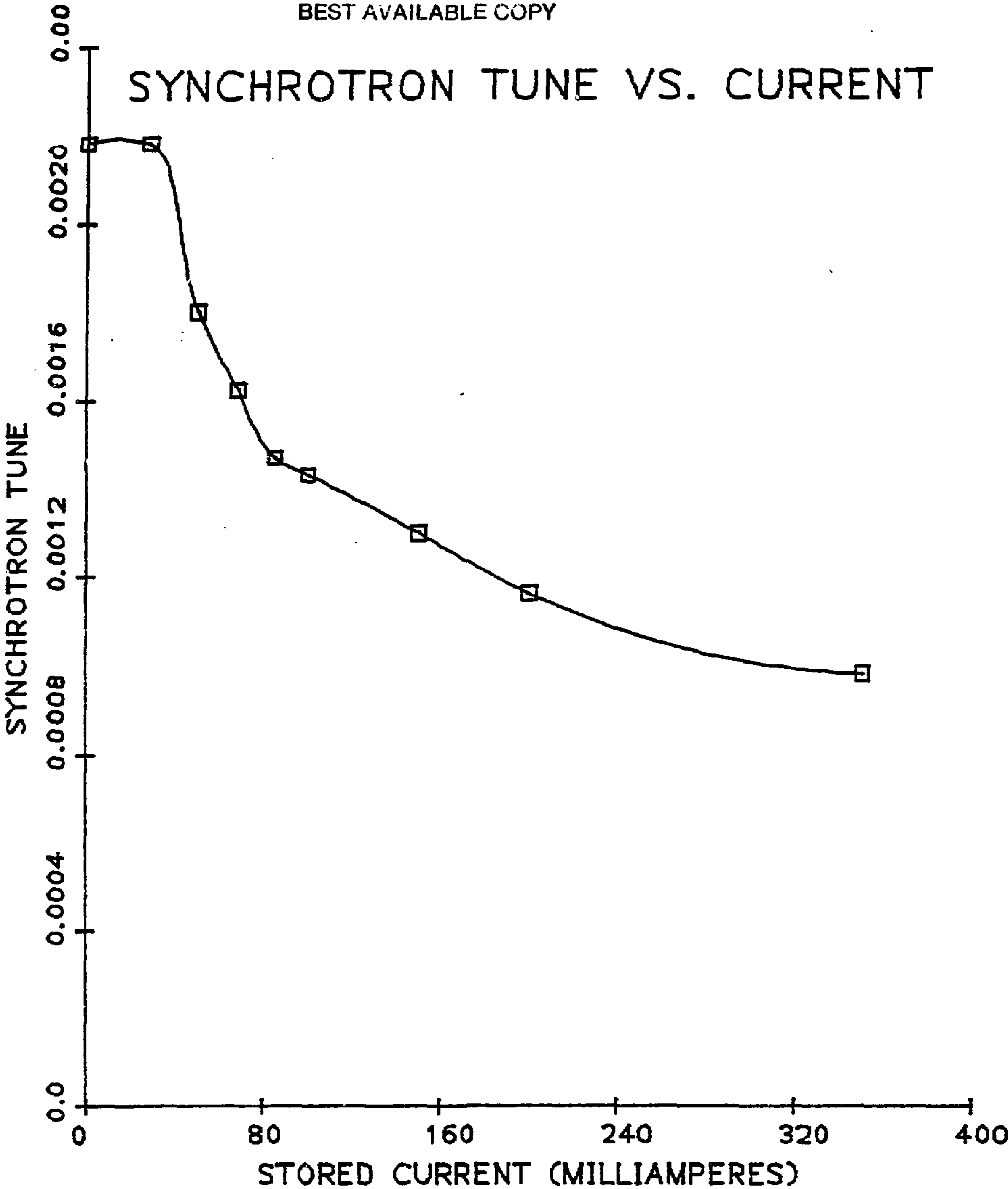

SYNCHROTRON TUNE VS. CURRENT
SYNCHROTRON TUNE
0.00
0.0020
0.0016
0.0012
0.0008
0.0004
0.0
0
80
160
240
320
400
STORED CURRENT (MILLIAMPERES)

FIGURE 2

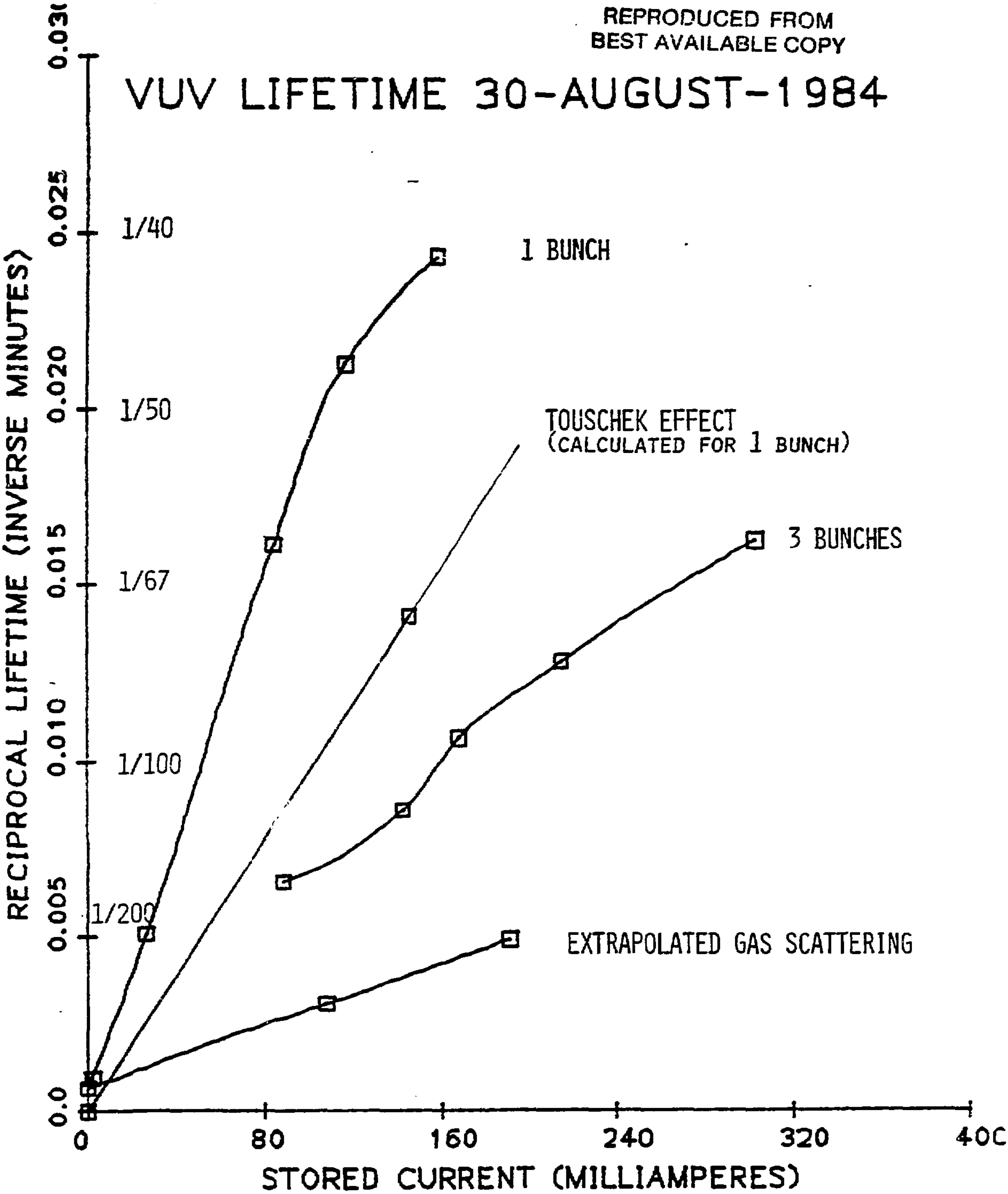
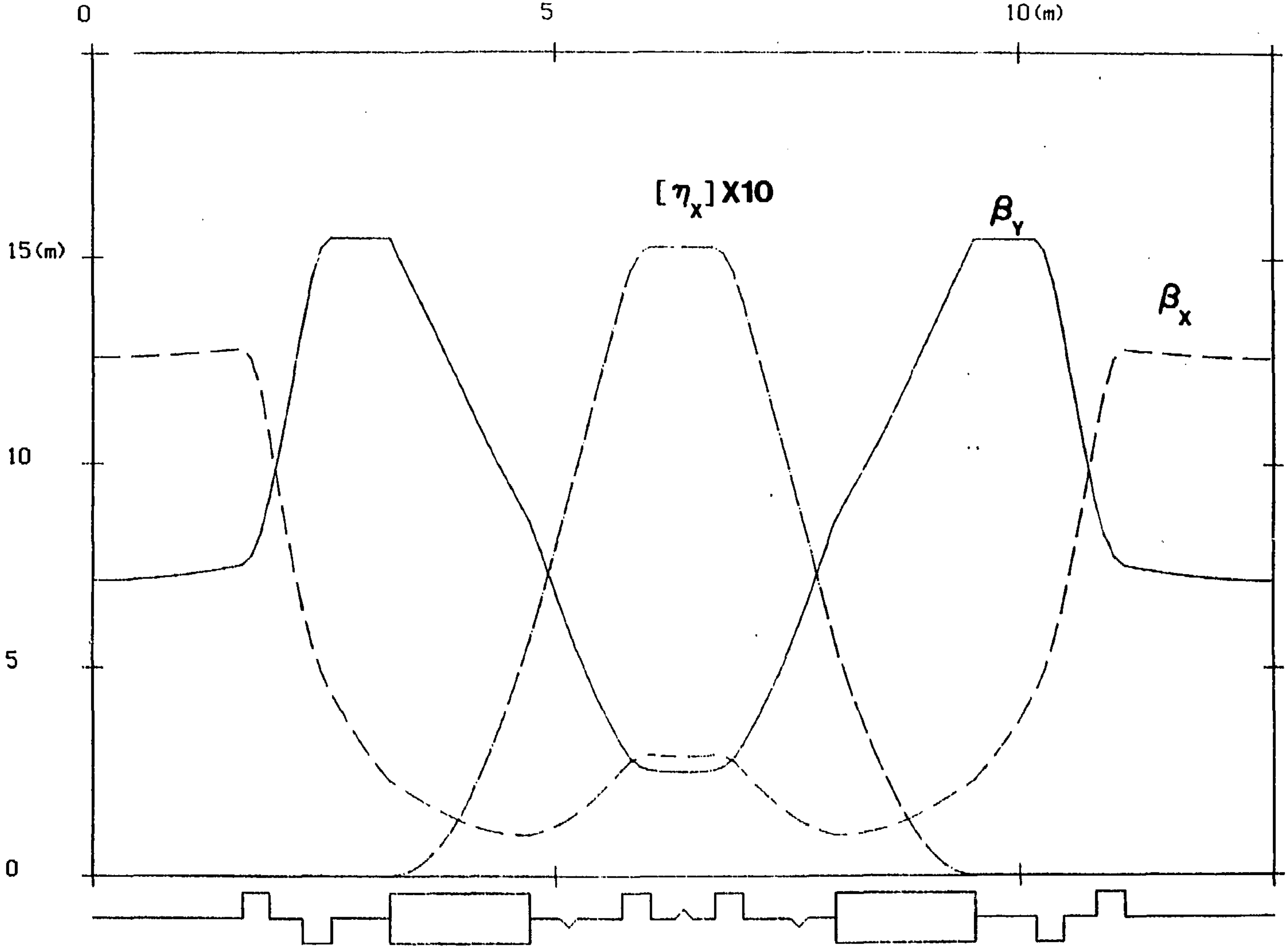

VUV LIFETIME 30-AUGUST-1984
RECIPROCAL LIFETIME (INVERSE MINUTES)
STORED CURRENT (MILLIAMPERES)
0.0
0.005
0.010
0.015
0.020
0.025
0.030
0
80
160
240
320
400
1/40
1/50
1/67
1/100
1/200
1 BUNCH
TOUSCHEK EFFECT
(CALCULATED FOR 1 BUNCH)
3 BUNCHES
EXTRAPOLATED GAS SCATTERING

FIGURE 3






VUV RING BETATRON FUNCTIONS

FIGURE 4