TRAPPED IONS AND BEAM LIFETIME IN NSLS STORAGE RINGS*

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Introduction

Ion trapping observed in most electron storage rings[1-5] causes various degree of deleterious effects both on brightness and on beam lifetime. Ion trapping is worst in the initial stages of operation when pressure due to synchrotron desorption is high. Based on these observations, various theories[6-10] to explain the phenomenon have been developed. Depending on specific machines and on the seriousness of their problem, individualized cures[5,10] have been adopted to eliminate or to cope with ion trapping. It is fair to say that the present understanding of ion trapping is incomplete partially due to lack of quantitative comparison between theory and experimental investigation and partially due to very different behavior among various machines.

In this paper we present preliminary results of our continuous studies to understand the ion trapping mechanism in the National Synchrotron Light Source (NSLS) electron storage rings.

Background

The limitation imposed on beam intensity by ion trapping was estimated by Robinson[6] on the Cambridge Electron Accelerator. The tune shift due to focusing force exerted by trapped ions has been the most widely used approach in studying this phenomenon both theoretically and experimentally in various machines for quite some time (1960 - present). For example, Jolivot[1] conducted cleaning current studies at Orsay's ACO, Kohaupt[5] studied the ion clearing mechanism for DESY's DORIS and Biagini[2] observed tune shift due to ion trapping at Frascati's ADONE. Baconnier[8] summarized ion trapping phenomena in a preliminary study for CERN's SPS $\bar{P}P$ collider. Recently in Japan, Kasugas et al.[5] reported their results of ion trapping effect in the UVSOR storage ring.

Low frequency oscillations induced by trapped ion are another method to investigate the effects of ion trapping employed by Bulyah[3] of Kharkov Physicotechnical Institute.

Based on the above mentioned observations, a generally accepted picture of ion trapping can be described as follows: as high energy electron bunches circulate through the vacuum chamber, they ionize residual gas molecules. The molecules with atomic mass higher than critical mass will be trapped in the potential well of the beam and will tend to neutralize the circulating beam. Based on the simplest model[9,11] full neutralization will occur in a few seconds if the residual pressure is in the 10^{-9} Torr range, see Table 1.

Table 1. Neutralization Time

	A	$\sigma(\mathrm{cm}^2)^2$	$\tau(\mathrm{sec})^1$
H_2	2	3.4×10^{-19}	0.29
CH_4	16	17.5×10^{-19}	0.06
H_2O	18	13.5×10^{-19}	0.07
CO	28	14.7×10^{-19}	0.07
CO_2	44	24.3×10^{-19}	0.04

1. See ref. 11, $\tau_i = \dfrac{1}{dm\, \sigma_i\, c}$

where $dm = 3.22 \times 10^{16} \times P(\mathrm{Torr})$

$C = 2.99 \times 10^{10}$ cm/s

$P = 1 \times 10^{-8}$ Torr

2. F.F. Ricke and W. Prepojdal, PR A6 (1972) 1507.

The critical mass, i.e. the minimum mass required for ions to be trapped in the potential well provided by the space charge force of circulating electron bunch, can be expressed in this simple model as:

$$A_c = \frac{n_p r_p}{n^2} \frac{\pi R}{\beta b^2 (1 + a/b)}$$

b = vertical transverse beam size
a = horizontal transverse beam size
R = machine average radius
r_p = classical proton radius
n^p = bunch number
n_p = number of circulating electrons
βc = velocity of circulating electrons

The effect of ion trapping on beam lifetime is recognized as a mixed blessing.[2] Its induced tune spread can raise the head-tail instability threshold by Landau damping, but at the same time the beam size grows and its brightness deteriorates. Besides the head-tail instability, the presence of trapped ions shifts the operating point[5] as follows: If the operating point is located below the resonance line, it moves toward the resonance line as trapped ions are accumulated. This is because the focusing force acting on the electron bunch provided by trapped ions is positive in both vertical and horizontal planes. As the operating point approaches the resonance line the beam size grows causing Landau damping to stabilize the beam and to suppress further tune shift. If the operating point lies above the resonance line, no stability mechanism such as Landau damping occurs and the beam becomes unstable. In addition, the electron beam interacts with trapped ion which lowers the lifetime through Bremsstrahlung and Coulomb scattering.[12]

Experiment

In order to gain a better understanding of the degradation in beam lifetime and brightness due to trapped ions, several kinds of clearing electrodes were employed in both the VUV ring operating at 750 MeV and the X-ray ring operating at 2.5 GeV. The general layout of these machines in the NSLS facility is shown in Fig. 1.

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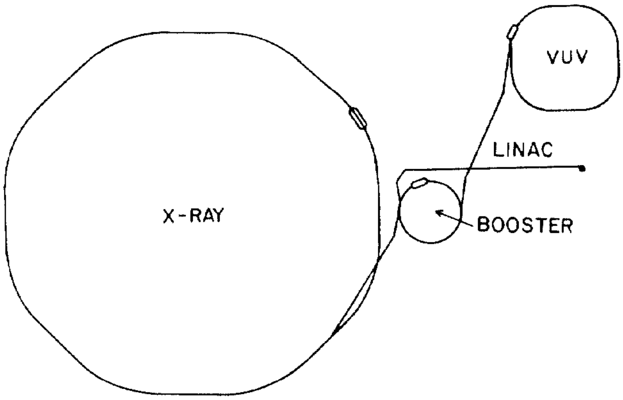

Fig. 1. NSLS General Layout

A. VUV Ring

Originally 16 locations, one on each side of eight bending dipoles, were provided for clearing electrodes (CE) during the construction, but they were not implemented. Due to space requirement for other diagnostic equipment, only 14 CE's were installed as shown in Fig. 2. The physical dimensions of CE are shown in Fig. 3.

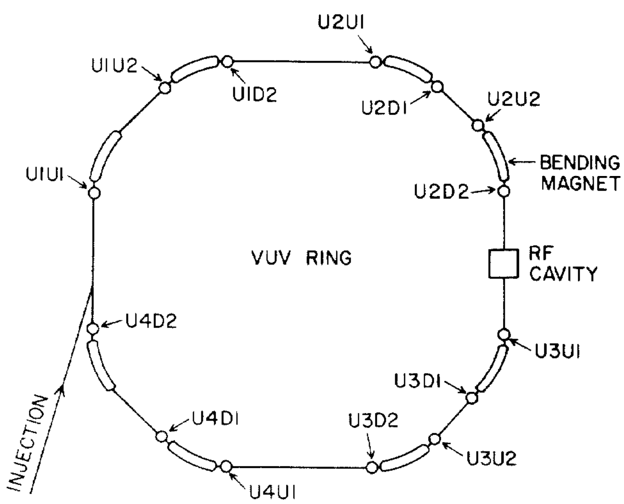

Fig. 2. Location of Clearing Electrodes at VUV Ring

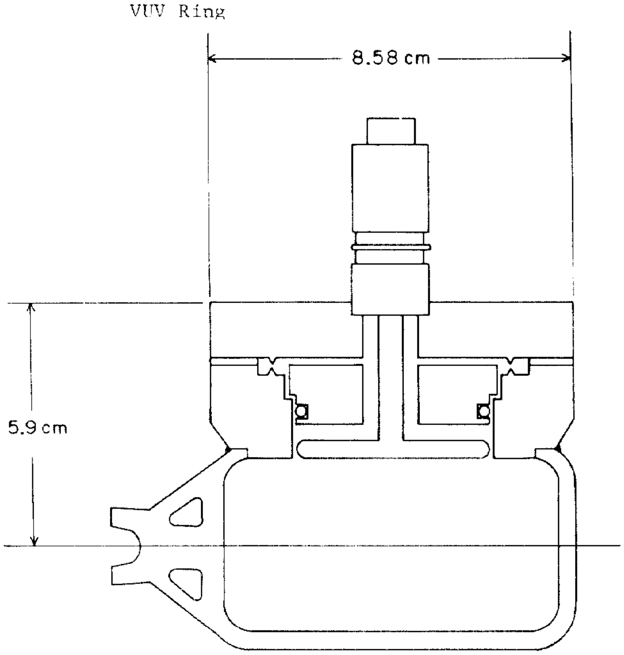

Fig. 3. VUV Clearing Electrodes

Since the CE's could act as high frequency antennas and affect adversely the operation of the storage ring, two kinds of termination were provided.

1. DC short circuit
   In this mode of operation, the CE's were grounded through a heavy conducting braid and no ion clearing was observed.

2. High frequency short using three capacitors (100, 1000 and 3300 pF) in parallel. During ion trapping experiment, CE's were connected through a 100 KΩ resistor and a current meter to a variable power supply (0 - ± 5 kV).
   This arrangement allowed us to measure both the copious photoelectrons produced by synchrotron radiation and positive ions with positive and negative polarity applied to the clearing electrodes, respectively. In addition to ion current, measurement of the onset of beam instability by ion trapping was observed using a beam size monitor.

B. X-Ray Ring

Two kinds of electrodes located at three positions (Fig. 4) were used to collect positive ions.

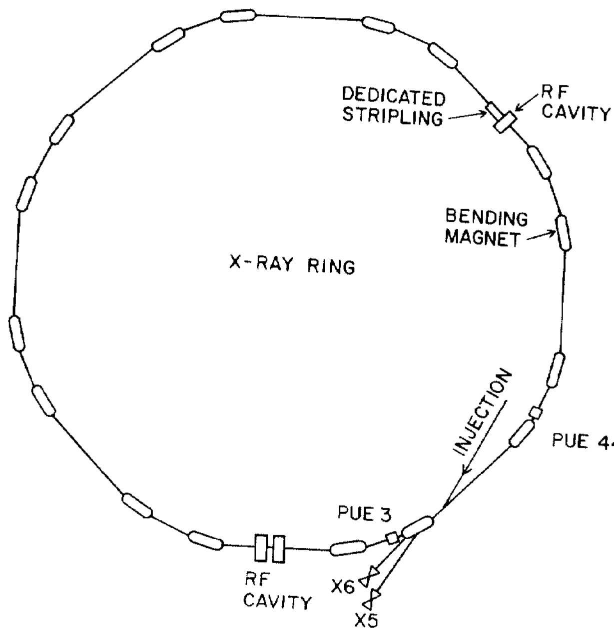

Fig. 4. Location of Clearing Electrodes at X-Ray Ring

1. A set of striplines shown in Fig. 5 were terminated in their characteristic impedance through a capacitance to permit operation with dc voltage up to 4 kV.

2. Two sets of pickup electrodes shown in Fig. 6 having dc breakdown voltage of 500 V.

The pressure in the striplines could be changed by operating the bleed valve as shown in Fig. 5.

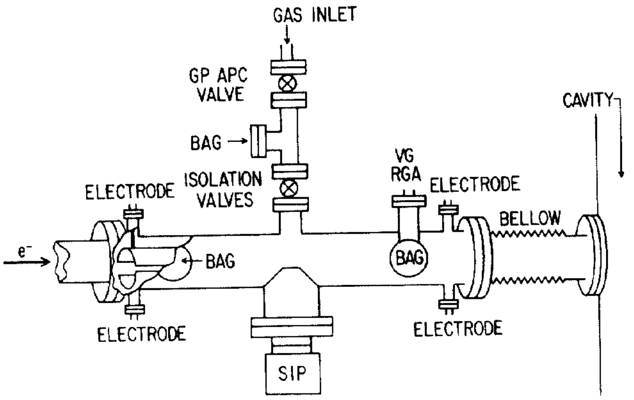

Fig. 5. Dedicated Stripline

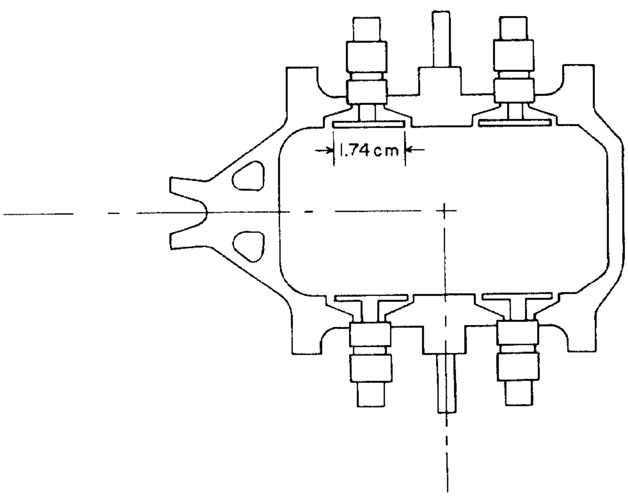

Fig. 6. PUE Electrode

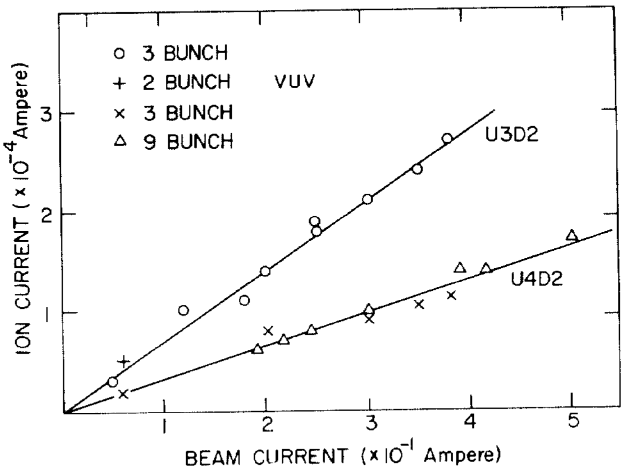

Fig. 7. Ion Current from VUV Ring

Results and Discussion

Table II gives typical results from the VUV ring. The full width of half maximum (FWHM) from the beam size monitor is used to monitor the onset of beam instability which critically depends on beam dynamic properties such as the operating point and machine optical properties. This could be the reason why onsets in the same bunch mode can differ substantially. For example, in three bunch operation, sometimes the instability appeared at 325 mA, while at other times, it could not be observed up to 710 mA, as shown in Table II. In the X-ray ring, within the available beam current (0-200 mA), so far we did not observe the instability induced by ion trapping. Table III shows the strong dependence of the ion current on PUE location. PUE3 is downstream of the bending dipole, while PUE44 is upstream of another bending dipole as indicated in Fig. 4. Several important results of the ion trapping experiment are summarized as below:

1. Ion current collected by cleaning electrodes (I_+) is proportional to the circulating electron beam, but is independent of its bunch structure as shown in Fig. 7 for the VUV ring and Figure 8 for X-ray ring.

2. The magnitude of I_+ is critically dependent on the location of the clearing electrode. It is larger downstream of the bending magnets and negligibly small at the upstream of bending magnets. In the x-ray ring I_+ is very large at the radio frequency cavity as shown in Fig. 8 and Table III.

Table II. Typical Experimental Result @ VUV Ring

Bunch Mode	Beam Current (mA)	Lifetime (min.)	Vert. Beam Size (mm)	(FWHM) (mm)	Ion Current U4D2 C.E. (μa)
1	155	110	1.0	2.0	
2	59	114			20
	247	40			100
3	50				18
	200		0.7	1.2	
	300				100
	325	65	0.9	1.5	108
	710		0.7	1.2	200
6	114				
	207		0.7	1.2	
	219		0.8	1.2	70
	234	92	1.0	1.2	
	286.4	320	1.3	1.2	130
7	113		1.3	1.2	
	204		1.5	1.2	
9	30		0.9	1.2	10
	100				30
	150		1.4	1.2	50
	216		1.6$_5$	1.2	70
	303		1.9^5	1.2	100
	415				140
	500	101	2.4	1.2	170

Table III. Results from X-Ray Ring

Bunch Mode	Beam Current (mA)	Life-Time (min.)	Positive Ion Current PUE 44 (μa)	PUE 3 (μa)	Strip-Line (μa)
5	26	1020			24
10	49	1129			45
	71	795			65
20	52	973			47
	100	1133			92
25	57	1352			92
	92				50
	100	346			86
28	160	550	0.12	2.7	160
30	45	1280	0.025		40
	100	632	0.070	1.7	93

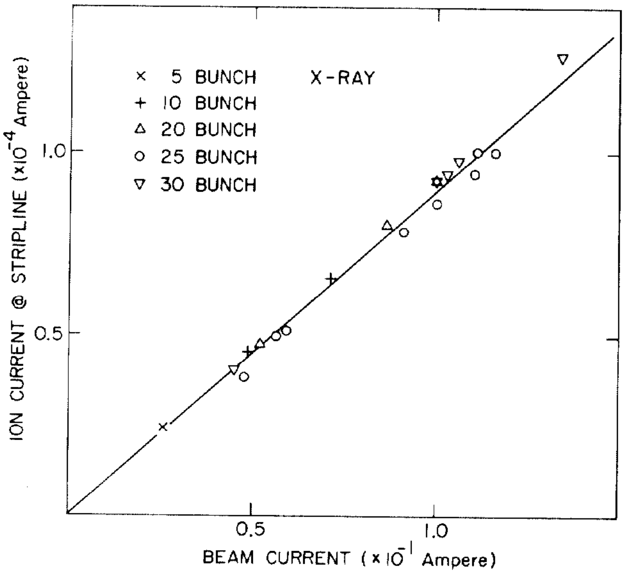

Fig. 8. Ion Current from X-Ray Ring

3. The magnitude of I_+ is independent of pressure introduced from an outside gas supply, but varies linearly with the synchrotron induced pressure rise.

4. The threshold stored beam current at which the beam blows up or the lifetime begins to deteriorate decreases with the increasing bunch number. Besides Coulomb scattering and Bremsstrahlung the lifetime and the brightness are determined in the UV ring primarily by a compromise between the trapped ions and the Touschek effect. In the X-ray ring where the Touschek effect is almost negligible, ion trapping is serious only in the early stages of operation when both the local and the average pressures are high. At present, the beam-gas lifetime is determined mainly by Bremsstrahlung and Coulomb scattering with an occasional trapped ion problem at high local pressure sites. Thus far our results can be correlated only very crudely with existing theories. We hope that with continuing studies we will gain a better understanding of this interesting phenomenon.

Acknowledgement

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