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ON-AXIS INJECTION SCHEME FOR ULTIMATE STORAGE RING WITH DOUBLE RF SYSTEMS

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Abstract

An on-axis injection scheme using double RF systems for an ultimate storage ring with very small dynamic aperture is proposed. By altering RF voltages, empty RF buckets can be created which will be used for on-axis injection. After bunches are injected, a reverse voltage altering process is performed and the injected bunches can be longitudinally dumped to the main buckets.

INTRODUCTION

A storage ring using "multi-bend achromat" (MBA) optics to reduce the natural emittance by one or two orders of magnitude down to current synchrotron light source storage rings has been proposed since 1995 [1]. After decades of efforts, this will become reality at MAX IV lab [2]. If the ring circumference is in the 1~2 kilometers range, the emittance of the electron beam will reach the photon diffraction-limited region for hard X-ray, an area that is of great interest to the synchrotron light community that could provide synchrotron radiation with high repetition rates and high brightness holding a large percentage of spatially coherent flux [3, 4]. A storage ring with these characteristics is called an "ultimate storage ring" (USR).

MBA optics employs much more numbers of bending magnets to decrease the bending angle θ of a single magnet and so reduce the natural emittance, which decreases as θ^3. Thus stronger quadrupoles are required to suppress the small dispersions created in the bending magnets, leading inevitably to the large negative native chromaticities in both transverse planes. In order to combat the head-tail instability and avoid large tune shifts of off-momentum particles, the chromaticities are usually corrected to slightly above zero, so strong chromatic sextuples are needed. These nonlinear elements will significantly reduce dynamic apertures presenting a great challenge for USR lattice design [5]. Many of the USR lattices which have been designed to date only provide horizontal dynamic apertures of around 2mm [6, 7, 8], leading to severe difficulties in injection.

One of the on-axis injection schemes, "swap-out injection", has been proposed [9], which uses a fast dipole kicker to inject fresh high charge beam onto the closed orbit while the stored beam is extracted. Swap-out scheme provides a baseline to inject the beam into the storage ring with a rather small dynamic aperture without major technical challenges. Recently, a novel longitudinal on-axis injection scheme was proposed in [10], in which a low frequency RF system is used, the bunch is injected at a phase with large deviation from the synchrotron phase and with energy slightly higher than the stored beam. Then the injected bunch damps to the synchrotron phase. For a storage ring with large energy acceptance this is a compact on-axis injection scheme without significant changing of the hardware.

In this paper, a possible approach for injecting beams into the USR, a new on-axis injection scheme is proposed. By altering the two RF voltages, empty RF buckets can be created which will be taken for on-axis injection. After bunches are injected, the voltage altering process will be reversed and the injected bunches can be longitudinally transferred to the main buckets (where the stored bunches are located). The energy oscillation of the injected bunches in this process can be controlled to less than 1%.

TWIN RF BUCKETS PRODUCTION

Assume that the storage ring has two RF systems, with the main RF system operating at 250MHz and the other one at the 2nd harmonic frequency 500MHz. The time dependence of the RF voltages are given by

$$V_m = \widehat{V_m}(st)cos(\omega_m t) \quad (1)$$

$$V_h = \widehat{V_h}(st)cos(2(\omega_m t - \varphi_s) - \pi/2), \quad (2)$$

$$\varphi_s = arccos(\frac{U_0}{\widehat{V_m}(0)}), \quad (3)$$

Where V_m, V_h are the voltage of the main and 2nd harmonic RF system respectively. The amplitudes of the RF voltages $\widehat{V_m}(st)$, $\widehat{V_h}(st)$ are modulated stepwise in a preset pattern. φ_s is the synchrotron phase of the main RF system, st denotes the modulating step, U_0 is the radiation energy loss per turn, and ω_m is the angular frequency of the main RF system.

If $\widehat{V_h}(st)$ is increased from near zero to its maximum value, while $\widehat{V_m}(st)$ is kept constant, one RF bucket will be split into two (twin) buckets as shown in Fig 1. As the stored bunches are located at synchrotron phases, they will be partitioned into two parts. In order to prevent the already stored bunches from being partitioned, a 'knot' as shown in Fig. 2 should be formed slightly before φ_s. The expression for the voltage of the second RF system should be modified to

$$V_h = \widehat{V_h}(st)cos(2(\omega_m t - \varphi_s) - \frac{\pi}{2} + \Delta\theta). \quad (4)$$

We call $\Delta\theta$ the synchrotron phase deviation and assume $\Delta\theta > 0$.

Figure 2 shows the detailed total voltage evolution process with $\Delta\theta > 0$. The stored bunch marked by the red dot will be pushed backward and the second empty RF

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bucket marked by the green dot will be created for on-axis injection. The temporal separation of the twin buckets is 1.5 ns when $\widehat{V_h}(st) = \widehat{V_m}(st)$. In order to increase the temporal separation of the twin RF buckets $\widehat{V_m}(st)$ can then be decreased. When $\widehat{V_m}(st)$ is decreased to near zero, the separation of the twin buckets will be around 2ns which will satisfy on-axis injection scheme with a TME RF kicker [11]. Since the created buckets are empty, the on-axis injection will not swap-out stored beams.

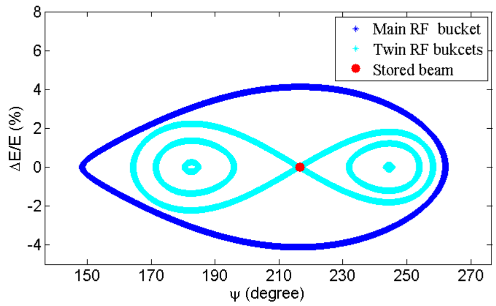

Figure 1: Twin RF buckets creation by two RF systems.

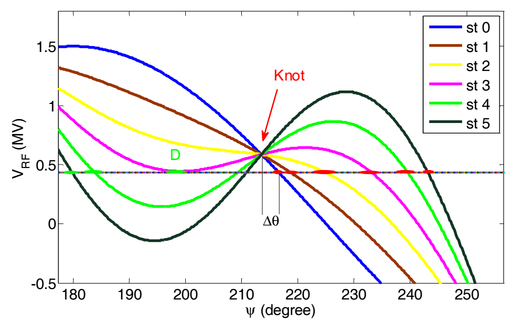

Figure 2: Twin RF bucket creation with synchrotron phase deviation. (From st 0 to st 5, the normalized RF voltages $[\widehat{V_m}, \widehat{V_h}]\ /\widehat{V_m(0)}$ is [1, 0.1], [1, 0.2], [1, 0.4], [1, 0.58], [1, 0.8] and [1, 1] respectively).

DUMPING OF THE INJECTED BUNCHES TO THE MAIN BUCKETES

Here we skip discussions on the transverse beam dynamics of on-axis injection using a fast dipole kicker, which can be found elsewhere [9, 11]. We will focus on the longitudinal beam dynamics of the injection process.

After bunches are injected and captured by the storage ring, a reverse RF voltage altering process will be executed. Assuming that the voltage altering period T_{RF} is on the order of seconds (much longer than synchrotron period τs) no sudden phase jump will occur, and the twin RF buckets will approach each other smoothly. The key step point (dumping point) is 'D' as indicated in Fig. 2. At this moment the injected bunches will be no longer stable in longitudinal phase space, and will experience synchrotron oscillations and eventually dumped into the main RF buckets. The oscillation amplitude should be minimized to lessen the impact on users and should also be within the energy acceptance of the storage ring.

The oscillation amplitude is relevant to the synchrotron phase deviation $\Delta\theta$. The smaller the value of $\Delta\theta$ the smaller the oscillation amplitude will be. However $\Delta\theta$ should be sufficiently large so as not to split the stored bunch. Taking the SSRF-UR (ultimate ring) parameters as an example, the stored bunches occupy 6 degrees in phase (1.96 times the RMS bunch length, 95% of the total beam charge), plus 0.5 degree phase jitter for both RF systems as a safety margin implies that Δθ should exceed 7 degrees (degree calculation based on 500MHz).

The main parameters of the SSRF-UR 7BA lattice are listed in Table 1. Longitudinal tracking can be performed using SSRF-UR beam parameters approximately with a steady state RF voltage at point 'D' because T_{RF}>>τs.

Table 1: Main Parameters of SSRF-UR (preliminary)

Lattice	**7BA**
E0	3.0GeV
C	432m
Emittance (pm)	205pm
$\nu_{x/y}$	47.19/12.13
Slip factor	2.2e-4
Vrf	1.5MV
Energy spread	0.08%

The tracking result shows that the energy oscillation amplitude at the dumping point 'D' is less than 1.0%. As shown in Fig. 3. The longitudinal phase acceptance is distorted into a teardrop shape from the nonlinear RF voltage.

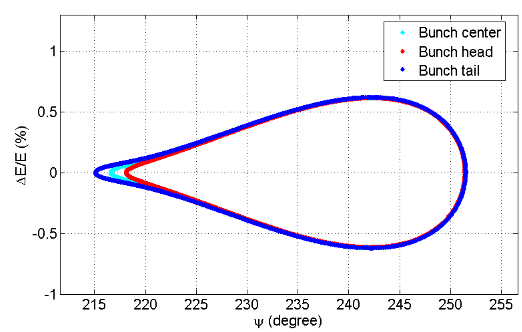

Figure 3: Tracking of longitudinal motion of injected bunch at the dumping point $\Delta\theta$=7 degree.

CALCULATION OF BUNCH LENGTH AND INTRA-BEAM SCATTERINNG

In a USR, the intra-beam scattering effect (IBS) will strongly influence the equilibrium emittance [2, 12]. IBS is highly sensitive to the bunch charge intensity in USR. As RF voltages are modulated in the process, the stored bunch length will change during the period. As a result, the bunch charge density and the IBS growth rate will be modified. To evaluate the effects of I BS, the bunch length evolution is calculated for a combined variation of

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$\widehat{V_m}(st)$ and $\widehat{V_h}(st)$ as listed in Table 2. The stored bunch length evolution during the RF voltage altering process is shown in Fig. 4. The bunch length becomes longer first as the slope of the RF voltage decreases and then is shortened as the 2nd harmonic RF voltage gets higher.

Table 2: V_m and V_h Variations as a Function of Step

step	**1**	**2**	**3**	**4**	**5**	**6**	**7**
$\frac{\widehat{V_h}(st)}{\widehat{V_m}(0)}$	0.1	0.2	0.3	0.4	0.5	0.6	0.7
$\frac{\widehat{V_m}(st)}{\widehat{V_m}(0)}$	1	0.95	0.9	0.85	0.8	0.75	0.7
step	**8**	**9**	**10**	**11**	**12**	**13**	
$\frac{\widehat{V_h}(st)}{\widehat{V_m}(0)}$	0.8	0.9	1	1	1	1	
$\frac{\widehat{V_m}(st)}{\widehat{V_m}(0)}$	0.6	0.5	0.4	0.3	0.2	0.1	

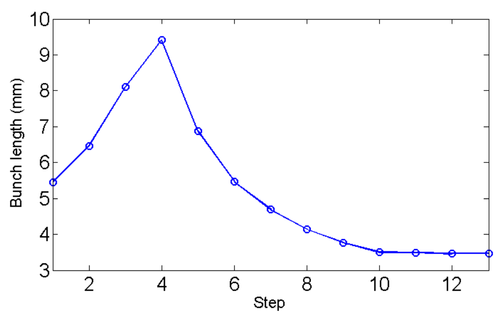

Figure 4: Bunch length evolution of stored bunch.

With a given bunch length as shown in Fig. 4, the IBS is evaluated by the code ZAP [13]. Figure 5 shows the equilibrium horizontal emittance counting IBS effect. During the injection process the emittance fluctuates about 10%, which will surely affect user experiments. Limited by its circumference, the SSRF-UR has a natural emittance of 205pm. At USRs with emittances of tens of pm, the IBS effect will be more severe, and the emittance fluctuation during the process will be bigger. The conservative way to mitigate this effect is sending a gating signal to the experimental hall to screen the data during injection.

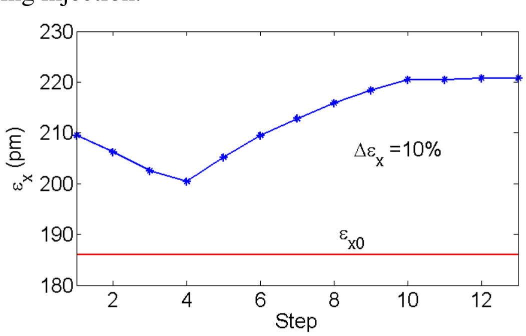

Figure 5: Equilibrium horizontal emittance during the injection process.

DISCUSSION

This injection scheme relies on alteration two RF system voltages. When the RF voltage approaches near zero it needs a large detuning angle for a smaller effect on the stored beam. This is the reason we propose an alteration period in the seconds range, leaving enough time for the detuning process. And zero voltage of both RF system should be avoided.

Actually this scheme will become very complicated when a 3rd harmonic cavity system is employed in low emittance rings to lengthen the bunch which is usually considered to decrease the IBS effect as well as to improve the Touschek beam lifetime. For this purpose, it can be found out that when the 2nd harmonic cavity parking at the working point with the voltage equal to 1/3 of the main RF voltage (step 3 in Table 2) will act as a bunch lengthening system.

It is mentionable that gap changes of insertion devices (IDs) will greatly affect USR performances as pointed out in [13]. The interplay of the ID gap change and the RF synchrotron phase shift will also affect this injection scheme. As suggested in [12] using a damping wiggler to compensate the radiation loss change caused by ID gap adjustment should be considered to stable the synchrotron phase.

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