ON-AXIS INJECTION SCHEME FOR ULTRA-LOW-EMITTANCE LIGHT SOURCES *

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Abstract

Injection design for an ultra-low-emittance light source is mainly limited by two effects. Due to intrabeam scattering and beam instabilities, multiple bunches with tight bunch spacing are injected into the ring to reach high average beam current, which limits the choices of injection technology. Strong non-linear effects due to the significant focusing force applied and the resultant strong sextupoles make the dynamic aperture very small, so that only on-axis "swap-out" beam injection is workable. Using a seven-bend-achromat (7BA) lattice designed for the Advanced Photon Source (APS) storage ring as an example, this paper presents an on-axis injection scheme based on the fast stripline technique together with discussions of the different configuration choices.

INTRODUCTION

When pushing a storage-ring-based light source emittance close to very low emittance, two primary consequences emerge: insufficient dynamic aperture for accumulation-based injection, so that only on-axis "swap-out" injection is workable [1]; and the maximum single-bunch intensity is significantly reduced due to the intrabeam scattering (IBS) and beam instabilities, so a significant fraction of the ring may need to be filled with beam to reach the required average beam current. Both factors put strict restrictions on the choice of injection technology and optics design.

In the scheme envisioned here, a single "swap-out" beam injection only replaces a portion of the stored beam, see Figure 1. The target bunches must be extracted and injected without affecting the emittance and stability of the remaining stored beam. For this to be the case, the kicker field must be negligible at the next upstream or downstream bunches, which requires kicker rise- and fall-times less than the spacing between bunches—usually one to a few rf buckets depending on the specific design, e.g., 10 rf buckets @500 MHz implies 20 ns. Commonly used ferrite kicker magnets cannot meet such requirements, but the stripline kicker technology proposed for the ILC damping ring [2] seems promising and is adopted in this paper.

A series of 40-sector, 6-GeV seven-bend achromat (7BA) lattices [3] have been studied for the future APS Upgrade. The lattice used is shown in Figure 2. In this paper, we will present an injection and extraction design for the 7BA lattice, with discussion of the different injection schemes.

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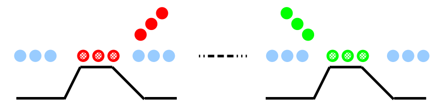

Figure 1: Sketch of on-axis "swap-out" injection (red: extraction bunches; green: injection bunches).

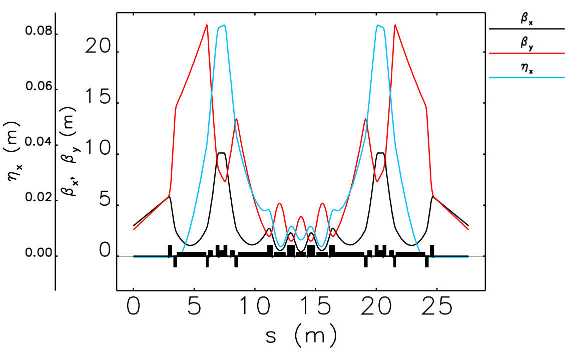

Figure 2: Single-cell optical functions of a 7BA lattice.

MAIN PARAMETERS

The kick angle from a stripline of length L with gap d between the electrodes is given by

$$\Delta\theta = 2g\frac{eV}{E}\frac{L}{d}, \tag{1}$$

where V is the voltage applied to the two electrodes, E is the beam energy, $g \leq 1$ is the geometry factor, and the factor 2 includes the force from both electric and magnetic fields. Using the stripline tested at ATF [4] (60 cm long, 10 mm gap, with $\pm$10 kV pulsers), the kick angle is 0.4 mrad.

The maximum achievable kick angle depends on two major factors: the available pulser strength V and the size of the stripline. Unlike the ILC damping ring, the required injection frequency is much lower, so a pulser with much higher output voltage [5] is available; V is then limited by the detailed design of the stripline (feed through). A smaller gap d increases $\Delta\theta$ for the same gap voltage V, while the maximum achievable V is also reduced due to reduction in the stripline size. As there is yet no detailed stripline design, we assume $V = 30$ kV at $d = 10$-mm gap compared with $V = 20$ kV at the same gap for the ILC damping ring. Larger L will make more efficient use of the limited space, but the maximum L is limited by the required rise/fall time. We choose $L = 0.6$ m, so that the rise/fall time is less than 5 ns. Altogether, the kick strength from a single stripline is 0.6 mrad. To accomplish the injection task, multiple striplines are needed.

Unlike other storage ring designs, an ultra-low-

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emittance light source like the 7BA discussed here usually has no more free drift space left inside the arc. The only space available is in the straight sections, which are mainly preserved for insertion devices. Assuming a single straight injection, the separation Δx between injected and stored beam center at the edge of the septum is given by

$$\Delta x \approx N\Delta\theta\frac{NL}{2} = \frac{\Delta\theta}{L}\frac{(NL)^2}{2}, \qquad (2)$$

where N is the total number of striplines and $\frac{\Delta\theta}{L}$ is the normalized kick strength in mrad/m.

The minimum separation Δx_{min} is given by

$$\Delta x_{min} = x_{inj} + x_{err} + s_a + s_d, \qquad (3)$$

where x_{inj} is the injected beam size, x_{err} is the allowed orbit error from all sources, s_a is the minimum septum aperture determined by other factors (for example, impedance), and s_d is the septum thickness.

Similar to the current APS design, two septums are used. We have set $s_a = 3$ mm and $s_d = 1$ mm for the thin septum in our simulation. The fully coupled injected beam emittance is assumed to be 30 nm. x_{inj} and x_{err} are related to the local beta function at the edge of the thin septum and will be discussed in later sections. All main parameters are listed in Table 1.

Table 1: Main Parameters for Injection

Title	Description	Value	Unit
General	Energy	6	GeV
	Stored Beam Emit.	81	pm
	Inj. Beam Emit.	30	nm
	Beta function at Inj.	≈3	m
	Orbit error (x_{err})	0.4	mm
Stripline	Length	0.6	m
	Gap	10	mm
	Gap Voltage	30	kV
Thin Septum	Length	0.25	m
	Thickness	1	mm
	Field Strength	0.7	T
	Inner Aperture	3	mm
Thick Septum	Length	1.5	m
	Thickness	2	mm
	Field Strength	1	T

BETA FUNCTION AT SEPTUM

A high-beta insertion is often used for the injection section design of a storage ring. Two pairs of kicks with phase advance close to π are located at either side of the septum, while the septum is located at the place of a high-beta function. The advantages of such a design are to minimize the kicker strength and reduce residual betatron oscillation of injected beam.

This kind of injection scheme is not applicable to the ultra-low-emittance light source (USR) for the following reasons:

- Phase advance. Since a light source tends to have a very crowded arc cell, there is insufficient space for multiple stripline kickers. Most likely, the stripline kickers will be placed in the same section as the septum.
- Optics perturbation. A specially designed high-beta injection section will break the lattice symmetry, which will typically reduce the dynamic aperture (DA) and momentum aperture (MA) significantly. Having sufficient DA/MA is already a big challenge for a USR lattice design.
- Impedance issues. Injection/extraction regions contribute a large portion to the entire ring's impedance budget. High-beta function makes the problem even more severe.
- Stripline aperture. High-beta function means larger beam size. Accommodation of the injection beam requires larger stripline gap, which reduces the stripline strength.

Due to the above reasons, a high-beta injection scheme was evaluated and abandoned. Those simulation results are not shown here. Note that if striplines and septum need to be put in the same section, then the beam separation is given by Eq. (2). From Eq. (3), a low-beta function at the thin septum, which minimizes x_{inj} and x_{err}, is preferable.

SINGLE STRAIGHT INJECTION AND EXTRACTION

If possible, putting injection and extraction to the same straight section is preferable. The minimum separation for beam extraction $x_{min,ext}$ is also given by Eq. (3) with replacing of x_{inj} to x_{sto} (beam size of stored beam). Using the parameters listed in Table 1, $x_{min,inj} = 5.3$ mm and $x_{min,ext} = 4.5$ mm. From Eq. (2), the minimum total stripline length for injection is 3.25 m, while the minimum total stripline length for extraction is 3 m. To accommodate the thin septum and including space between each element, ~ 1 m of extra space is needed. Thus a minimum 7.5-m-long straight section is required to accommodate both on-axis injection/extraction in one straight section for a 6-GeV ring. Since the straight section length of our design is 5.8 m, injection and extraction require separate straight sections. In our design, sector 38 is used for beam extraction and sector 39 is used for beam injection.

SEPARATED INJECTION AND EXTRACTION

As just discussed, injection and extraction need to be separated into two sectors. The difference between injection and extraction is that the required minimum separation at the thin septum is slightly different. For simulation

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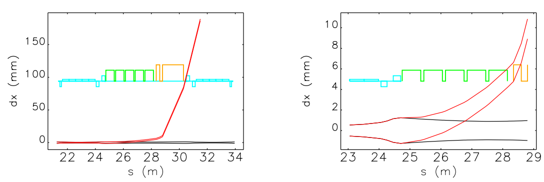
convenience, we illustrate here the extraction line using parameters of beam injection as listed in Table 1.

To allow a 3-mm inner aperture for the thin septum, a minimum 5.3-mm beam separation must be provided by the stripline kickers. This number assumes 1-mm septum thickness, 3 sigma of injected beam size ($\sigma = 0.9$ mm at $\beta_x = 3$ m), and 0.4-mm orbit error from various sources. Using a normalized kick strength of 1 mrad/m, the total stripline length is 3.25 m from Eq. (2), requiring five 0.6-m-long striplines. Figure 3 shows the extraction line configuration (injected beam is from right to left), the envelope of injected beam (red line), and the envelope of the first turn of injected beam. This plot also shows why high-beta injection is not preferable, because in that scheme the stripline gap has to be increased to accommodate the entire injected beam envelope, which becomes much wider when using high-beta injection. Since now the minimum aperture limitation around the ring is the thin septum (3 mm), some stripline apertures (for example, 1 and 2) could be reduced to increase the normalized kick strength. The potential benefit from reducing stripline aperture is limited by the feedthrough, so this must be evaluated when we have a detailed stripline design. The separation at the first quadruople is 0.1 m and needs to be considered in the magnet design.



(a) Inj. layout (b) Zoom In

Figure 3: Injection configuration: black - first turn injected beam, red - injected beam, green - stripline, and yellow - septum.

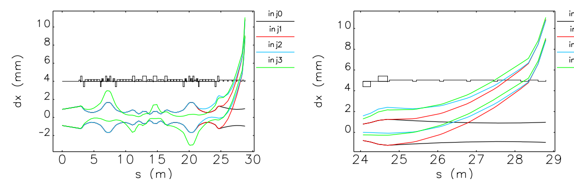
OTHER CHOICES

Besides putting all injection elements into the same straight section, other injection schemes have been studied. For example, we looked at putting striplines in the arc where sufficient drifts are present or using the straight section in the next sector. Results are shown in Figure 4.

The effectiveness of these choices strongly depends on the detailed optical design, i.e., the phase advance between the thin septum and an available space for installing an extra stripline. One could make this a special requirement to the optical design, or modify the existing optical design to make a special section to suit the required phase advance. Other issues make such choices unwelcome, including:

- Broken symmetry. It makes the already challenging nonlinear effects correction even more difficult.
- Less flexibility. A modification of the optical design will require a re-design of the injection line. It becomes more difficult due to the strong nonlinear effects.
- Large orbit oscillation inside arc, see Figure 4. This also causes nonlinear effects and may harm injection efficiency.

These effects can be seen from Figure 4. The additional stripline inside arc (inj2) doesn't increase beam separation at the septum due to the wrong phase advance. The additional stripline installed in other sectors (inj3) does increase beam separation at the septum at the expense of large orbit oscillation inside the arc, which means every change of the chromaticity configuration could result in rematching of the injection line. We have abandoned such options due to unclear benefits and these potential problems.



(a) Overview of different injection schemes (b) Zoom in of different injection schemes

Figure 4: Comparison of different injection schemes: inj0 - first turn injected beam, inj1 - all stripline in one straight, inj2 - one stripline in arc, inj3 - one stripline from the next sector. See how beam orbit varies inside the arc (a) and beam separation at the thin septum (b).

CONCLUSION

Using an APS 7BA lattice design as an example, several on-axis injection schemes have been studied. Results reveal the possible choice of injection technology, the main parameters determining the injection design (injection beam size, minimum septum aperture, etc.), and as a consequence, the requirements on the optics design (drift space, beta function, etc.). Our results show that on-axis injection into the 7BA lattice can be achieved. We attempted to make our discussions here as general as possible, so results can be used for other USR designs.

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