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HIGH-CHARGE INJECTOR FOR ON-AXIS INJECTION INTO A HIGH-PERFORMANCE STORAGE RING LIGHT SOURCE*

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Abstract

Next-generation, high-performance storage ring (SR) light sources based on multibend achromat optics will require on-axis injection because of the extremely small dynamic aperture. Injectors will need to supply full-current bunch replacement in the SR with high single-bunch charge for swap-out. For upgrades of existing light sources, such as the Advanced Photon Source Upgrade (APS-U), it is economical to retain the existing injector infrastructure and make appropriate improvements. The challenges to these improvements include achieving high single-bunch charge in the presence of instabilities, beam loading, charge stability and reliability. In this paper, we discuss the rationale for the injector upgrades chosen for APS-U, as well as backup and potential alternate schemes. To date, we have achieved single-bunch charge from the injectors that doubles the original design value, and have a goal to achieve about three times the original design value.

INTRODUCTION

Many synchrotron light source facilities are pursuing the development of multibend achromat (MBA) storage rings, either on a green field [1-3] or as upgrades to existing facilities [4-11]. An MBA can reduce the horizontal emittance by 1-2 orders of magnitude compared to a third-generation synchrotron of the same circumference, thereby increasing the x-ray brightness dramatically. The emittance and transverse acceptance tend to be correlated [12], and this presents a challenge for injection. Some MBA designs under development plan for off-axis accumulation, which typically require a low-emittance injector or incorporate new ideas, such as using an anti-septum [11]. Higher-performance MBA designs, i.e., those approaching 2 orders of magnitude emittance reduction, require on-axis injection.

The most straightforward on-axis injection scheme is swap-out, where the injectors produce enough single-bunch charge to perform complete bunch replacement [13]. Alternatively, there are a number of schemes under study to determine the feasibility of on-axis injection with accumulation. Examples include off-momentum injection [14], rf manipulation [3], or using a nonlinear kicker [15].

A comprehensive evaluation of the various injection schemes was recently reviewed [12] and is beyond the scope of this paper. Instead, we focus on meeting swap-out injector requirements for a high-performance MBA upgrade to an existing facility. Swap-out places the highest demand on injector bunch charge. We use the example of APS-U to describe how the challenging demands on the injector were addressed, given the constraints of the existing infrastructure.

DESIGN CHOICES FOR INJECTOR

It can be cost-effective upgrade the injector while keeping its basic structure. There is no single solution, but rather a set of design choices based on feasibility and practical considerations. While APS-U is a specific case, upgrade ideas could be translated to other facilities. In the following sections, we discuss the rationale for the baseline and backup upgrade plans, as well as alternatives.

The basic layout of the APS injectors for APS-U is shown in Fig. 1. The linac provides 1-nC pulses at a 30-Hz rate. Up to 20 pulses are accumulated and damped in the particle accumulator ring (PAR) [16] at the fundamental rf frequency. In the final 230 ms of the 1-s cycle, the single bunch is captured in a 12th harmonic rf system and the bunch length is further compressed. The bunch is injected into the booster where it is ramped to full energy and extracted into a transport line that was redesigned for matching into the MBA storage ring (SR) [17].

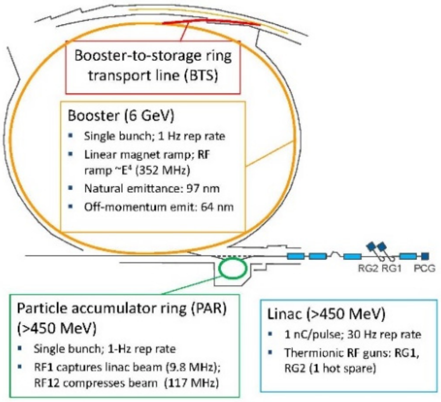

Figure 1: APS-U injector complex.

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The APS-U injector performance requirements are summarized in Table 1. The charge goals correspond to the timing mode, or 200 mA in 48 bunches. The injector can also provide 5-nC "guard" bunches adjacent to ion-clearing gaps for the brightness mode: 200 mA in 324 bunches [4].

Table 1: APS-U Injector Performance Requirements

	APS	Achieved	Goal
PAR charge	2-4 nC	20 nC	20 nC
Booster charge	2-4 nC	12 nC	17 nC
SR charge (injected)	Accum.		16 nC
Charge stab. (rms)	<5 %	2-10%	5%
BTS ε_x at 6 GeV*	<64 nm		<60 nm
BTS ε_y at 6 GeV	~6 nm		<16 nm

* Natural emittance at -0.6% momentum offset for APS and -0.8% momentum offset goal for APS-U.

The MBA SR will operate at a higher rf frequency than the booster (the circumference is smaller than APS SR). A new injection timing and rf distribution system will enable synchronized bunch-to-bucket transfer between the booster and the MBA SR [18]. Decoupling the rf systems enables the possibility of ramping the rf frequency in the booster, allowing injection into the booster close to on-momentum, while extracting the beam farther off-momentum. On-momentum injection maximizes the capture efficiency for the high-charge bunch from PAR. Off-momentum extraction takes advantage of damping partition manipulation to lower the emittance for efficient MBA injection. All injector upgrades are planned to be completed prior to removal of APS and installation of the MBA SR in 2022. An alternative to the injection synchronization scheme is realignment of the booster. However, this introduces an undesirable schedule risk, since the booster would need to be re-commissioned at the same time as the MBA SR.

ACHIEVING HIGHER CHARGE

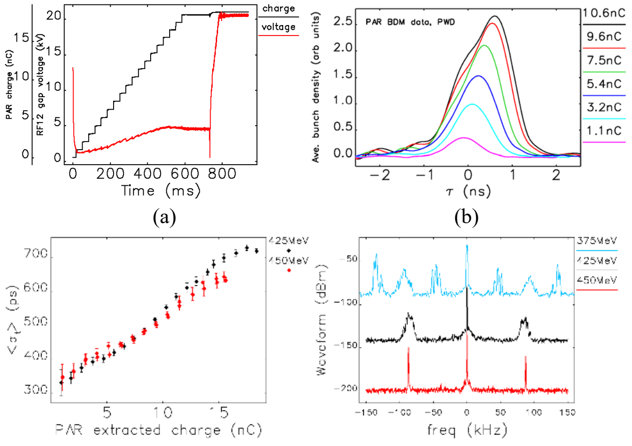
Timing mode swap-out calls for injected bunch charge that is nearly three times higher than the original APS injector design charge of 6 nC. PAR and booster diagnostics upgrades were essential for characterizing and optimizing high-charge beam. High-charge optimization includes PAR harmonic rf tuner and amplitude feedforward, adjusting booster rf voltage at injection, optimizing orbit bumps and orbit correction, and chromaticity correction. Impedance models did not exist for the injectors, and were completed for booster [19] (PAR model is on-going). Machine models were verified using response matrix analysis [20].

Diagnostics

Digital low-level radiofrequency (LLRF) diagnostics installed in booster and PAR are used in on-going rf system optimizations at high charge. A prototype PAR fundamental LLRF system is being tested, and plans for PAR harmonic and booster LLRF and feedback systems are ongoing. Bunch duration monitors (BDM) installed in both PAR and booster give turn-by-turn measurements of the bunch length [21]. Charge-dependent longitudinal bunch spectra analyses are ongoing to determine the source of the observed bunch oscillations. New digital cameras installed on all existing synchrotron light ports enable high-fidelity beam size measurements at low- and high-dispersion source points. Turn-by-turn BPMs in PAR show charge-dependent injection transients but no transverse instability.

Instabilities

In PAR, lower-charge dynamics are dominated by potential well distortion (PWD), while higher-charge dynamics appear to be dominated by microwave instability. Significant bunch lengthening and synchrotron sidebands are observed at high charge (Fig. 2c,d). Before an impedance model was available, a simple R, Z circuit model was developed by fitting the measured bunch distributions (Fig. 2b) to the Haissinski equation. A beam energy 450-500 MeV is predicted to be sufficient to raise the instability threshold to 18-20 nC. With the beam in a linear or nearly linear regime, higher harmonic rf gap voltage should reduce the bunch length at high charge and better match the Booster acceptance. The harmonic rf amplifier will be upgraded to higher power to meet this requirement.



(a) (b)

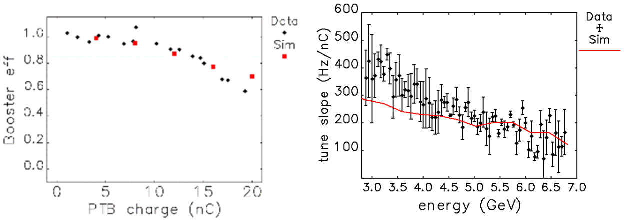
(c) (d)

Figure 2: PAR measurements: (a) charge and harmonic rf waveform over cycle, (b) bunch distributions, (c) rms bunch length, and (d) longitudinal bunch spectra for 16nC.

A nearly-completed PAR impedance model identifies bellowed flanges and flag chambers as comprising about 50% of the loss factor; thermal sensing of vacuum chamber components confirm high charge-dependent heating at these locations. Component redesigns are under study. PAR instability modeling is underway and will be used to inform what linac and PAR beam energy is required and whether a vacuum chamber upgrade is required. A linac upgrade that supports APS-U is also planned.

An alternative to stabilizing the PAR beam is to stack two 8-nC bunches (with relatively short bunch length) from PAR in the booster. This would require a current-regulated controller for the booster dipole power supply, which would also improve injection efficiency and charge stability, and is a potential future upgrade.

A mature booster model includes transverse and longitudinal impedance, injection errors, beam loading, and injected beam parameters [19]. Injection modeling shows very good agreement with measured efficiency (Fig. 3a; 85% goal is marked). Simulations predict no transverse instability up to 20 nC, and no instability is observed up to 12 nC. Refinement of the model is planned as higher-charge is achieved in booster. The impedance model gives reasonable agreement with the measured tune shift with charge (Fig. 3b). Analyses are on-going to measure the booster emittance, using a recently-installed YAG screen in the BTS emittance diagnostic station. These measurements will be cross-checked with a synchrotron light monitor that was upgraded in the booster.



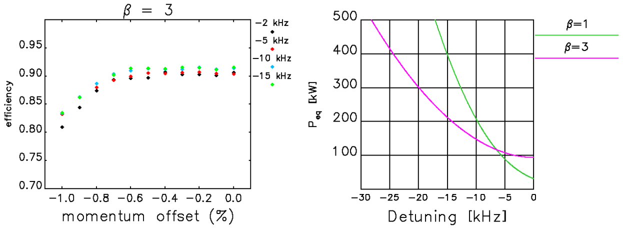
(a) (b)

Figure 3: Booster simulations agree well with the data: (a) injection efficiency and (b) vertical tune shift with current.

Beam Loading in Booster

Beam loading is a serious concern in booster at injection, and was studied with particle tracking simulations. The best performance is achieved with on-momentum injection and detuning of the cavities at injection. Since the required frequency sweep is positive, the cavities will be further detuned at extraction (for static tuners), which results in high reflected power. Large detuning at extraction demands new rf couplers that can handle high equivalent power. A ferrite-based dynamic tuner design is also being developed as an alternative [22].

Simulation shows that beam loading can be mitigated by over-coupling the cavity (β=1 → β=3), so large detuning would not be needed (Fig. 4a). Over-coupling the cavities reduces coupler power for large detuning. At 300 kW and β=3, the total detuning range (injection detuning + frequency sweep) is -20 kHz (Fig. 4b). For -0.8% momentum offset at extraction, simulations give 90% injection efficiency for injection detuning of -2 to -15 kHz, with injection momentum offsets of -0.27% to -0.65%, respectively.



(a) (b)

Figure 4: (a) Simulations of booster efficiency vs injection detuning and momentum offset. (b) Equivalent power as a function of detuning, coupling coefficient, and charge.

CHARGE STABILITY

Charge stability is < 0.4% rms from the thermionic gun at equilibrium. For well-tuned conditions, PAR and booster charge stability is 2-5% rms. The main challenges include controlling the PAR instability and injection into booster. An upgrade of the booster BPMs and corrector controllers enabled correction of the orbit over the ramp (Fig. 5), which improved high-charge efficiency by a few %.

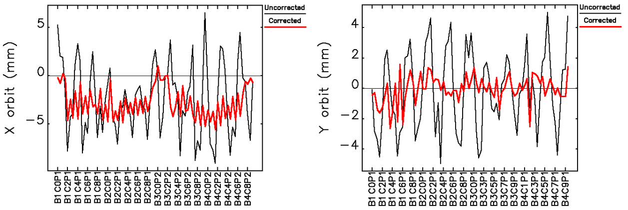


Figure 5: Booster orbit correction after BPM and corrector improvements; horizontal (left) and vertical (right) plane.

BEAM LOSSES

APS-U must consider the potential for higher injector beam losses during normal operation as well as possible missteering events. Supplemental shielding analysis is on-going in PAR using both loss measurements and radiation modeling with MCNP [23]. Booster shielding was determined to be adequate. A fiber-based beam loss monitor was installed as a diagnostic [24].

CONCLUSION

Swap-out injection places a high demand on single-bunch injector charge for a future high-performance MBA storage ring light source. Several design choices are possible to meet the requirements, assuming upgrade of an existing facility.

The APS-U injector upgrade and alternatives were presented as feasible solutions in the case of a timing mode, which requires 16 nC injected bunch replacement in the MBA SR, and up to 20 nC in the injectors (giving an overall 80% efficiency budget). Single high-bunch injector charge also enables special fill patterns, such as higher-charge “guard” bunches adjacent to ion-clearing gaps.

Improved diagnostics were key to understanding and controlling the injector beam. Upgrades are needed in PAR and booster to meet the high charge and emittance requirements, and a linac energy upgrade is also required. A new injection timing and rf generation system enables bunch-to-bucket transfer with booster and the MBA SR at different rf frequencies; it also supports Booster high-charge capability. The goal is to implement all injector upgrades prior to MBA SR installation, and for the injector beam to be ready for MBA commissioning.

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