CREATION OF HIGH-CHARGE BUNCH TRAINS FROM THE APS INJECTOR FOR SWAP-OUT INJECTION*

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Abstract

A multi-bend-achromat (MBA) low-emittance lattice is being explored for a future APS Upgrade [1]. Due to its small dynamic aperture, the traditional injection scheme must be replaced with a "swap-out" scheme [2]. Several options were considered for the creation of a high-charge bunch train from the injector, and we selected an option that builds the bunch train in the existing particle accumulator ring (PAR). This option enables both single-bunch mode, which is necessary to support current APS operation, and bunch-train mode. This report provides a description of the injection process, simulation results, and specifications of injector timing, kicker, and rf subsystems.

INTRODUCTION

The APS injector consists of a 450-MeV electron linac, a particle accumulator ring (PAR), and a synchrotron booster. The PAR has a 9.77-MHz cw fundamental system (RF1) and a 117.3-MHz pulsed 12th-harmonic system (RF12). In the first 250 ms, beam is accumulated into the RF1 bucket and damped to a bunch length of ~0.86 ns. RF12 is turned on at 250 ms of the PAR cycle and compresses the bunch length to 0.3 ns. Bunch cleaning is performed at 350 ms, and beam is further damped and extracted at 483 ms. Currently the injector runs at a 2-Hz rate and provides a single bunch with a beam charge of up to 4 nC. For an APS MBA low-emittance lattice, the injection scheme would be replaced with a single-bunch or bunch train swap-out scheme. Several bunch fill patterns are being considered: a single-bunch high-charge mode with up to 4 mA per bunch, and a multiple bunch mode that consists of multiple bunch trains, each with up to 5 bunches per train.

HIGH-CHARGE SINGLE-BUNCH AND BUNCH TRAIN GENERATION

The APS MBA upgrade now under exploration envisions two types of fill patterns: a 48-singlet fill pattern with a single-bunch charge of up to 15 nC, and a multi-bunch-train fill pattern with up to 432 bunches.

For 48-singlet mode the injector would need to deliver up to a 20-nC single-bunch with an emittance of 30 nm-rad in the x and y planes. The rf gun, without major upgrade, can deliver about 1 nC per pulse with 30-Hz repetition rate. To reach 20 nC we would need to extend the PAR accumulation cycle from the current value of 0.5 second to 1 second or longer. Figure 1 shows a possible 1-second PAR accumulation cycle. During the first 633.33 ms, 20 linac pulses are accumulated, while the next 100 ms is used to damp the beam to about 0.8 ns in length. The 12th-harmonic rf is turned on around 733.33 ms, following which the beam is captured into the 12th-harmonic bucket and compressed to a bunch length of 0.3 ns. Bunch cleaning is then turned on for 20 ms. After a final damping of 100 ms, beam is extracted to the PAR-to-booster (PTB) beam transport line. The current rf system, with modest upgrades, can support this operating cycle.

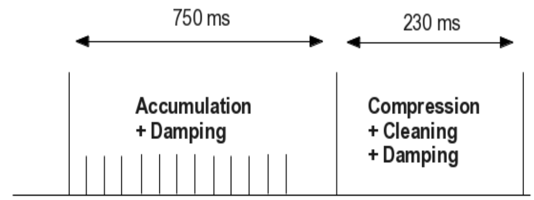

Figure 1: Accumulation of high-charge single-bunch beam in the PAR.

For the multiple bunch-train fill pattern, we consider 2 to 5 consecutive bunches per bunch train with a total of up to 432 bunches and flexible spacing between the trains. To build such bunch trains the PAR rf system must be replaced with a cw 352 MHz system. The bunches can be either accumulated one at a time with a linac micro-bunch length of less than 1.5 ns, or simultaneously with a long linac micro-bunch of up to 15 ns. In both cases a fast gun chopper with a rise time of ~1 ns is needed to accurately control the length of the linac micro-bunches. Bunch cleaning can be performed after accumulation to remove unwanted satellite bunches. Figure 2 shows one possible bunch-train fill pattern with 4 bunches per train.

Figure 2: A multiple bunch train fill pattern.

TIMING SYSTEM UPGRADE

The APS timing system would need to be upgraded to accommodate the new fill patterns and timing precision requirements. The "swap out" mode of operation and ns-level rise/fall time of the kickers requires much-reduced jitter time, estimated to be 50 ps or lower. The jitter time of the existing APS timing system, measured in the range of 200 to 500 ps, is apparently inadequate. A new timing infrastructure would need to be developed to achieve the required timing precision.

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STORAGE RING KICKER UPGRADE

The swap out injection scheme [3] requires extracting an old bunch or an old train of bunches and replacing it with a new one. The spacing between the singlet bunches or bunch trains can be as short as two or three buckets, i.e., 5 to 8 ns. The rise time and fall times must be shorter than this spacing. Since traditional ferrite-based kickers would not provide such fast response, we are exploring the use of multiple striplines driven with very fast pulse generators, e.g., similar those made by FID GmbH [4]. For on-axis injection we would need a 3-mrad total kick angle. A set of seven striplines could be used for injection with a total length of 2.8 m. Another set would be used for extraction. Development work on the stripline kicker is underway. Table 1 lists the main parameters for the stripline kickers.

Table 1: Main Parameters of the Stripline Kickers

Impedance (Ω)	Drive voltage (kV)	Kick angle (mrad)	Total kick (mrad)	Total length (m)
50	±20	0.4	3.0	2.8

RF POWER AND DETUNING REQUIREMENTS FOR HIGH SINGLE-BUNCH CHARGE

At 20-nC single-bunch charge the PAR average current is 200 mA and we expect to see much stronger beam loading effects. Upgrades of rf amplifiers and tuning loops would be needed to compensate for the high beam loading. The booster rf system (RF5) would also need to handle a beam current of 17 mA. An estimated 450 kW of rf power is required at extraction, 50 kW more than the current value, and much higher detuning is required at injection. Table 2 lists the required rf power and detuning angle for the upgraded rf systems. Based on these estimates, the current cavities, the RF1 amplifier, and the RF5 klystron can support the required power. The amplifier for the PAR RF12 system would need to be upgraded, and the detuning range for the PAR cavities must be measured and re-evaluated. The booster cavity uses mechanical tuners that can only react to slow changes. The large detuning range between the injection and extraction of the booster beam may require a fast tuner. We are considering installing ferrite tuners through a coupler installed in one of the ports of the cavity. If that is not practical then direct rf feedback must be considered to stabilize the beam.

Table 2: Rf Power and Detuning Requirements

System	Gap Volt V(kV)	Shunt imp. Rs (MΩ)	Power P (kW)	Detuning ψ (deg)
RF12	30	0.22	4.2	40
RF1	40	0.37	4.8	40
RF5@inj	620	221	1.8	80
RF5@inj	9000	221	460	20

Figure 3 and 4 shows the estimated power and detuning for the PAR RF12 system.

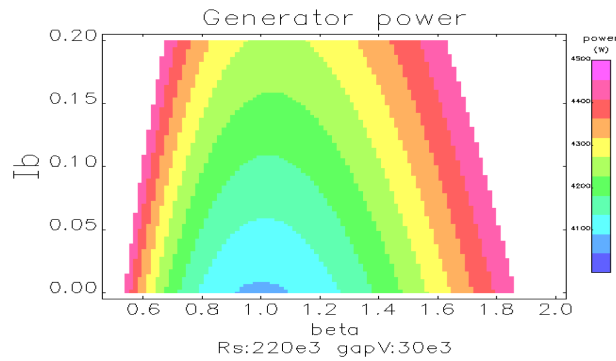

Figure 3: Power requirement as a function of beam current and coupling coefficient for RF12.

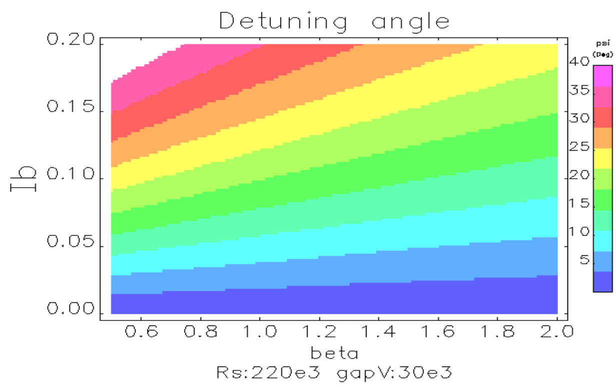

Figure 4: Detuning requirement as a function of beam current and coupling coefficient of the RF12 cavity.

BEAM INSTABILITIES

Resistive-wall, coupled-bunch, and ion instabilities are stronger with higher single-bunch charge. Chromaticity correction is perhaps the most effective compensation method. For the PAR, the sextupole magnets and corrector magnets are combined. A current limit of 4 A limits the chromaticity to 1 or 2 in both planes, even though the sextupole power supply can provide more than 10 A. We will perform magnetic measurements and evaluate the feasibility of increasing the sextupole current limit to 10 A, which will bring the chromaticity to 6 to 7. The booster sextupole magnets, especially the defocusing sextupoles (SD), are currently close to their power supply limit. We would need to upgrade these supplies to increase the sextupole field by a factor of 1.2 to 1.5. Pole-tip shimming is also being considered. Simulations show that adding 3-mm shims to the poles increases the sextupole field by 30%. Combining these two methods should give a 50% increase in booster sextupole strengths for a target chromaticity of ~7 in both planes.

Transverse feedback systems would need to be installed for both the PAR and booster in case dynamic aperture becomes a limiting factor with increased chromaticity.

BOOSTER BEAM EMITTANCE

The beam emittance of the booster 92-nm lattice, measured at the current energy of 7 GeV, is 72 nm-rad.

The reduction in emittance is due to momentum offset caused by rf frequency change. At 6-GeV extraction energy of the APS MBA lattice, the booster emittance would be reduced to 53 nm-rad, much higher than the sub-100 pm MBA lattice emittance. Since the MBA lattice uses on-axis injection and also has nearly equal β-functions for both x- and y-planes, we can further reduce the effective booster emittance by full coupling. A study shows that full coupling can be realized by moving the booster tunes together along the ramp cycle. Figure 5 shows a tune measurement result. We measured a reduction of x-emittance by a factor of two. Hence, we anticipate that we can achieve a booster emittance of 30 nm in both planes.

BOOSTER RAMP SUPPLY UPGRADE

The booster ramp supplies employ 12-phase-SCR-based voltage regulation hardware. Current regulation is achieved with workstation-based ramp correction programs. The system runs well for normal operations. However the supplies, especially the dipole supply, are sensitive to AC line harmonic distortion and line voltage changes. To insure the stability and reliability of injector operation we may need to replace the power supply with switching-type power supplies with current regulation.

In addition, the corrector ramp control hardware would be upgraded to achieve a ramp update time of 1 to 2 seconds, which would enable us to run orbit correction with sufficient speed.

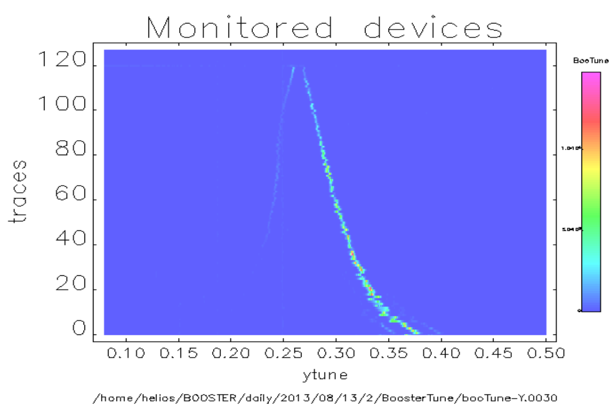

Figure 5: Tune plot of a fully coupled booster beam. The bright trace is the horizontal tune and the dim trace on the left is the vertical tune. Each trace represents 1.8 ms in time.

LINAC SYSTEM UPGRADE

The APS linac consists of dual thermionic rf guns and a photocathode gun, two non-SLEDed klystrons (L1 and L3), and three SLEDed klystrons (L3, L4, and L5) delivering a maximum beam energy of 450 MeV. During normal operations the linac delivers a 375-MeV beam. High single-bunch charge injection may require running the linac with more pulses per cycle and a beam energy of 450 MeV. This may impact linac reliability, so we may add a waveguide switching network so a spare klystron (L6) can be a hot spare for the L4 or L5 klystrons. A kicker that serves as a bunch length chopper, which has a rise/fall time of 50 ns, would be upgraded with a new power supply giving few-ns rise and fall times, in order to accurately control the linac micro-bunch length.

BEAM DIAGNOSTICS UPGRADE

The PAR beam position monitors (BPMs) have a strong beam intensity dependence and can only be used for slow orbit correction in a limited beam current range. New BPM electronics would be needed to increase the dynamic range of the BPMs. The new system would also provide turn-by-turn history capability for beam physics studies, e.g., analysis of instabilities and potential cures.

The booster BPM system was designed to read the average orbit at one time slot during a ramp. It can only be used to tune up beam orbit. A new booster BPM system would use the same BSP-100 module [5] used in the APS storage ring. The new system would provide averaged orbits for up to five time slots along the acceleration cycle, allowing orbit to operate continuously. The orbit correction program could be configured to treat each of the combinations of BPMs and time slots as an independent variable. Turn-by-turn histories would also be available for such tasks as injection trajectory correction, beam stability analysis, etc.

CONCLUSIONS

An MBA extreme low-emittance lattice is being explored for a future APS upgrade. A “swap out” scheme with a high-charge singlet fill pattern and a multiple-train hybrid fill pattern are under consideration. We considered the options and necessary upgrades in order to prepare the injection beam with the existing APS injector complex.

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