

# UPGRADE OF THE APS BOOSTER SYNCHROTRON MAGNET RAMP\*

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## Abstract

The APS booster is a 7-GeV electron synchrotron with 0.5-second cycle time. Both voltage and current ramp modes were in the original design but only the voltage ramp has been commissioned. Two software-based ramp control programs are used to regulate the current waveform to a linear ramp. The system has been operated for user beam operations for many years. Some instability exists in the ramp correction that requires manual intervention from time to time by the operators. Sensitivity of magnet currents to external changes, such as AC line voltage and harmonic interference from the high-power rf system, has been observed. In order to meet the increased single-bunch-charge requirement of the APS upgrade we need more flexible current ramps such as flat porches for injection and extraction, and smooth transitions. Recent efforts to develop an energy-saving operation mode also call for ramp improvement. This paper presents recent improvements of a workstation-based current regulation program and an FPGA-based implementation as a future upgrade.

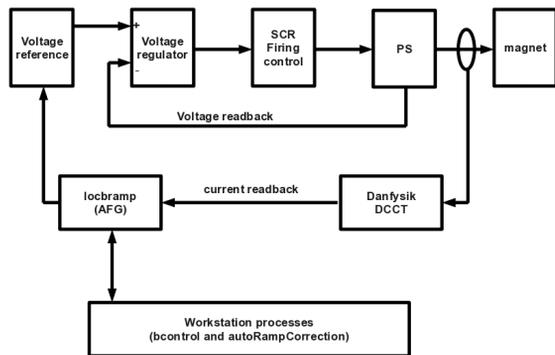


Figure 1: Block diagram of the voltage regulation system of booster ramp supplies.

## INTRODUCTION

The APS booster has five magnet families that are powered by five main ramping power supplies. Only voltage regulation is implemented currently in the supplies. Voltage reference waveforms are generated by workstation-based high-level applications and are pre-loaded to the arbitrary function generator (AFG) modules of the EPICS-based ramp control local input-output controller (iocbramp). Gain and delay of AFG output waveforms are separately adjusted with a gain and a trigger process variable (PV) [1,2]. In order to correct for

errors due to external perturbations, such as perturbations and distortions of AC line voltage, or temperature changes of the magnets and supplies, we use two workstation-based programs: `bcontrol` that adjusts AFG trigger and gain PVs to maintain the linear-fit slope and zero-cross of the current waveform, and `autoRampCorrection` that manipulates the voltage reference waveform to minimize the rms linear-fit errors of readback current waveforms. Figure 1 shows a block diagram of the ramp control and regulation system, and Table 1 shows a list of nominal parameters of the booster magnet system.

This system has been in place for many years, and the booster has worked reasonably well providing beam for user operations. However, a ramp correction instability exists that causes a constant shift of ramp timing and booster efficiency drop requires periodic manual intervention by the operators. A recent lab-wide energy conservation initiative also calls for development of an energy-save mode of the booster dipole supply, which demands stability of the ramps while the ramps are cycled on and off.

Table 1: Nominal Magnet Parameters of APS Booster

	Dipole	QF	QD
Max. curr. @inj. (A)	42	30	30
Max. curr. @ext. (A)	902	610	610
Inductance (H)	0.664	0.0529	0.0617
Resistance (Ω)	1.278	0.842	0.969
Required resolution	$2 \times 10^{-5}$	$5 \times 10^{-5}$	$5 \times 10^{-5}$

## UPGRADE OF RAMP CORRECTION ALGORITHM

In order to find the cause of the instability in the BM ramp correction we applied singular value decomposition (SVD) analysis on a set of ramp reference data accumulated over several days. We found that the most important component, namely SV001, is directly correlated to BM trigger time shift. Figure 2 shows the correlation between the SV001 component and the BM trigger changes, and the spatial pattern of the SV001 component. The spatial pattern very much resembles the derivative of a voltage reference waveform. Voltage reference waveforms are only manipulated by

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autoRampCorrection while BM trigger time is only modified by bcontrol. This correlation shows a coupling exists between these two correction programs or their input variables.

Several algorithms of the ramp correction programs were analyzed, modified, and tested. We found the original normalization process, which normalizes the amplitude of the rising part of voltage reference waveform to a constant, is responsible for most of this coupling. A new normalization is implemented that zeros out any changes in the DC component, or average value, of the voltage reference. After the change, the trigger time shows an oscillation pattern and is no longer an operational problem.

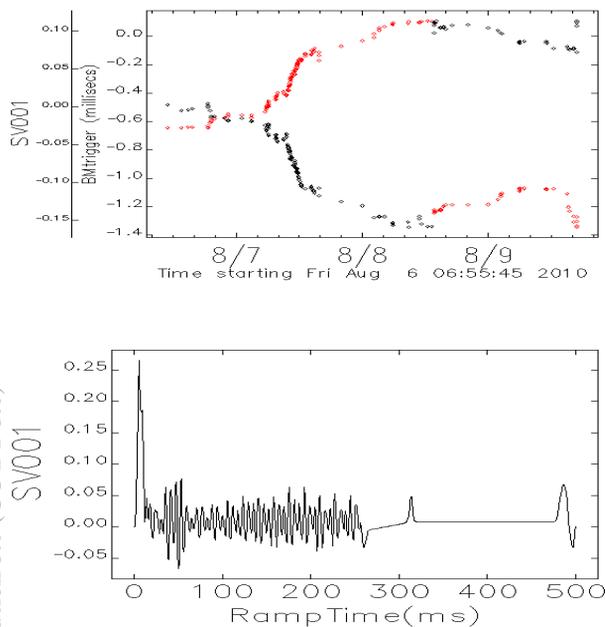


Figure 2: Top: a plot showing the correlation of BM trigger (black) and the amplitude of the SV001 mode (red). Bottom: spatial waveform of the SV001 mode.

## DEVELOPMENT OF “SMOOTH” RAMP

The booster accelerates beam from an injection energy of 325 MeV to 7 GeV in 223 ms. At low energy the required current tolerance is 21 times lower than it is at extraction energy. The original voltage reference waveform has a fast voltage rise before the linear part of the ramp. A current transient exists due to this fast voltage rise, which causes inconsistency in beam capture. To reduce the transient we developed a “smooth” ramp, which replaces the voltage rise with a 16-ms or longer linear voltage front segment. Figure 3 shows the simulated voltage and current waveform of the smooth ramp with different lengths of the front segment.

Ramp correction process involves linear-fitting of the readback current waveform and correcting the residual current errors. This is necessary because of the overall scheme of separately correcting slope and zero-crossing, and waveform errors. Special care must be given to the beginning and end of a ramp, where current waveform

deviates increasingly from the linear-fit line. The original ramp correction employs a linear-weight approach that reduces the weight function gradually from 1 to 0 in that transition period. This approach is effective in reducing transition glitches in the corrected voltage reference. However, it produces predictable bell-shape glitches at both ends of a ramp. To reduce this effect, and to accommodate the new “smooth” ramps, we developed a new approach that extends the linear fitting to the transition period with a linear-voltage-fit front segment, essentially preserving the “smooth” feature in the corrected voltage reference. This fit method applies the same algorithm that generates the “smooth” ramp. The new algorithm helps to reduce the transient effect and works well with “smooth” ramps.

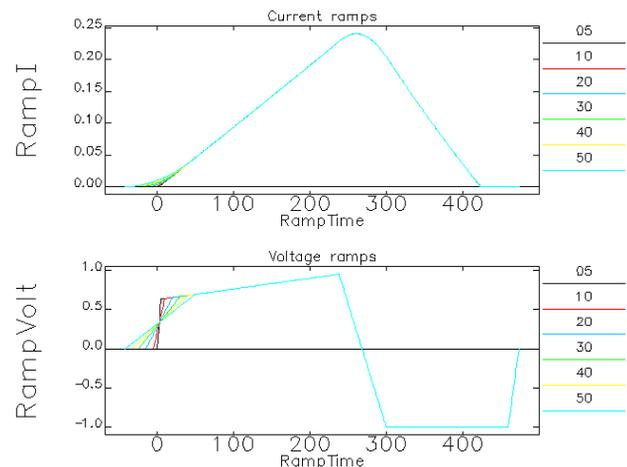


Figure 3: Simulated current and voltage ramps with lengths of front segment varying from 5 to 50 ms. Legend is the front-segment length in ms.

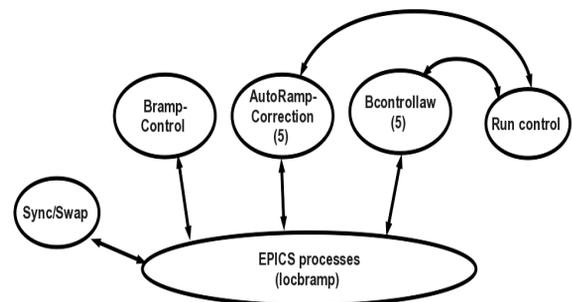


Figure 4: A block diagram of the new ramp correction configuration.

## UPGRADE TO CONTROLLAW-BASED BCONTROL PROCESS

The original bcontrol program is designed as a dedicated C program that performs one-dimensional correction to slope and zero-crossing. APS has a generic controllaw program [3] that has been applied to many areas, such as storage ring orbit correction, injector trajectory correction, etc. The benefits of upgrading to a

controllaw-based program are that will: (1) enable correction with 2-by-2 matrix; (2) simplify operation procedure; and (3) reduce software maintenance.

Ramp current response to AFG gain and trigger-time changes are measured with a generic response measurement tool. All the magnets show cross-response of zero error to gain change. This cross coupling is especially strong for the BM and SF. Figure 4 shows the new controllaw-based ramp correction configuration.

### REDUCTION OF 360-HZ RIPPLES IN DIPOLE POWER SUPPLY

We identified the sources of a 360-Hz harmonic ripple in the booster dipole magnet supplies; it is due to the AC coupling through the ground protection circuit and the capacitance between the magnet core and coil. A higher-impedance protection circuit was installed, and we observed obvious improvement in the tune spectrum of the booster beam after the installation.

### PRESENT RAMP PERFORMANCE

Performance of the ramp supplies has improved significantly. Figure 5 shows a recent dI/I measurement results. The quads have met our specification. The dipole still needs some improvement, especially at low energy.

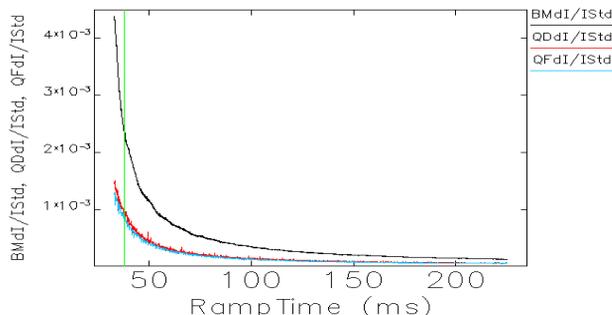


Figure 5: Measured dI/I standard deviation of the booster ramp supplies. The vertical green line marks the injection time.

### DEVELOPMENT OF ENERGY-SAVING MODE FOR THE BOOSTER DIPOLE

The APS booster ring dipole magnet power supplies use about 500 kW of power on average to support the storage ring top-up operations. In theory, much of this power could be saved if the ramp is turned off when injection is not required. Several energy-saving schemes are being considered including running the injector with 1-Hz instead of 2-Hz, running all the ramp supplies on/off, and only turning off/on the ramp of the booster dipole. We adopted the last scheme because it is relatively easy to do and may be achieved without any hardware upgrade.

A `boosterEnergySaveMode` program was developed that monitors the progress of top-up cycles, turns off the ramp for 1 minute after a top-up shot, and

turns on the ramp for 1 minute. We found that ramp correction could not keep up with the thermal cycle of the power supplies and magnets. In order to keep the current waveform within tolerance at injection time we need to optimize the restart time of the ramp correction. Some magnet power supplies show noticeable coupling with the dipole power supplies, and their ramps are perturbed by turning the dipole ramp on and off. This problem is remedied by stopping their ramp correction when the dipole ramp is off, preventing it from making unnecessary and wrong corrections.

Figure 6 shows a plot of rms current error during a test period. This mode is now the standard user operation mode for the 24-singlet fill pattern.

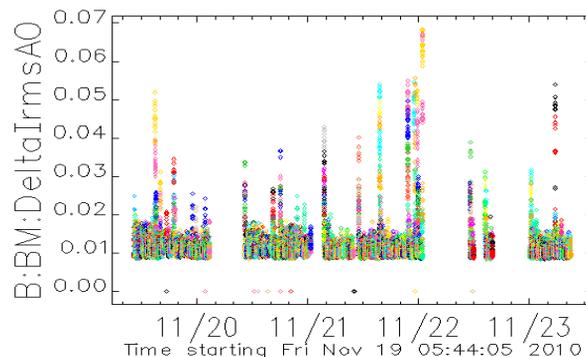


Figure 6: Booster BM percentage delta-I/I rms logged data during energy-saving test. Typical value for operation is around 0.01%. The spikes are right after turning on the ramp.

### FURTHER IMPROVEMENTS

There are several options we want to explore for further improvements: 1) upgrade of the power supplies to hardware-based current regulation and 2) upgrade of the SCR firing card in the power supplies to achieve better control resolution.

### ACKNOWLEDGMENTS

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