A PHYSICS BASED APPROACH FOR RAMPING MAGNET CONTROL IN A COMPACT BOOSTER *

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Abstract

At Duke University, a booster synchrotron was recently commissioned as part of the High Intensity Gamma-ray Source (HIGS) upgrade. For the ramping magnet power supply controls, a scheme was developed to present the high level operator interface in terms of the physics quantities of the accelerator, i.e. the effective focusing strength of the magnets. This scheme allows for the nonlinearities of the magnets—a result of the extremely compact footprint of this booster—to be incorporated into the low level software. This facilitates machine studies and simplifies the use of physics modeling. In addition, it simplifies operation, allowing the booster to ramp to any energy from the 0.24 GeV of the injector linac to the 1.2 GeV maximum of the Duke storage ring. The high level of flexibility of this system is further advanced by incorporating the level of tunability typically found in a storage ring control system. Tuning changes made during steady-state operation are automatically propagated to the waveforms which make up the booster ramp. This approach provides a good match to the wide operation modes of the Duke storage ring and its associated free electron laser (FEL), and may be useful for other compact booster synchrotrons.

INTRODUCTION

The Duke booster synchrotron (Table 1) has been designed to provide top off injection to the Duke storage ring over the energy range of 0.24 to 1.2 GeV. The booster can ramp to any energy within this range with 1 MeV resolution. The control system for the booster, developed with the Experimental Physics and Industrial Control System (EPICS) toolkit, allows for a great deal of flexibility [1]. The ramp cycle time can be adjusted, allowing power supply settling or beam damping time before injection, before ramping or before extraction. Injection has been demonstrated from 0.24 to 0.27 GeV. Extraction has been demonstrated over a number of energies up to 1.2 GeV. The booster has been operated in single electron bunch, two bunch and nineteen bunch modes. With more than one electron bunch in the booster, bunch by bunch extraction can run at any frequency up to 25 Hz, limited by the kicker repetition rate. Any electron bunch within the booster can be extracted to any electron bunch in the storage ring allowing for any arbitrary fill pattern of the sixty-four storage ring buckets. The booster controls also allow for a high degree of tunability of the magnetic elements, allowing for dynamic tuning of the ramping waveforms. The booster was successfully commissioned in 2006 [2] with the control system and all major hardware functioning as designed.

Table 1: Basic operational parameters of the Duke booster

Injection energy:	0.24–0.27 GeV
Extraction energy:	0.24–1.2 GeV
Maximum beam energy:	1.2 GeV
Extraction energy resolution:	1 MeV
Minimum operation cycle:	1.3 seconds
Energy ramp up rate:	1.5625 GeV per second
Energy ramp down rate:	3.125 GeV per second
Circumference:	31.902 m
Bending radius:	2.273 m
Peak dipole field (1.2 GeV):	1.76 Tesla

IMPLEMENTATION

In a previous system upgrade, the Duke storage ring magnetic element controls were implemented in such a way that the high level operator interface was presented in terms of the physics quantities of the accelerator [3]. Rather than presenting magnet controls in terms of power supply current, the system presents magnetic elements in terms of their effective focusing strength. Such an approach allows for a tighter integration between the physics model of the accelerator and the operating machine. It also simplifies the implementation of feed forward compensations, allowing the Duke storage ring to be tuned over a wide range of energies and FEL wiggler settings.

The Duke booster synchrotron continues this approach. Although elaborate feed forward schemes as used in the storage ring are not necessary, this approach simplifies tuning of the machine and has proven to be useful during commissioning and during routine operation. The control system for the booster allows for a level of tuning more typical of a storage ring. The booster's energy ramp can be stopped at any energy within its operation range, at which point the machine can be tuned with stored beam, adjusting orbit, tunes, chromaticity, etc.

High Level Controls

The Duke booster is very compact with a circumference of only 31.9 meters. This small footprint requires high field dipole magnets of 1.76 Tesla leading to significant saturation at the higher energies [4]. By presenting the operator

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interface in terms of the effective focusing strength of the magnets, the nonlinearities due to saturation can be effectively compensated within the lower level software. This results in nearly energy independent tuning as seen from the high level controls. Tuning adjustments made to the machine in non-ramping mode are automatically propagated to the ramping waveforms, with appropriate energy dependent compensations. In this way, new ramping waveforms can be tested and developed using stored beam and then be immediately available for ramping operation.

For standard ramping operation, the operator can specify injection energy (corresponding to linac injector energy, typically 0.24 to 0.27 GeV) and extraction energy (corresponding to the storage ring energy, 0.24 to 1.2 GeV) in 1 MeV steps. The booster can then be run in a semi-autonomous manner for either single shot or continuous injection, or top-off mode to maintain a given storage ring electron beam current. The ramp cycle, starting at injection energy, consists of injection from linac to booster, ramp to extraction energy, extraction from booster to storage ring, ramp to full energy for magnet normalization, and then ramp to injection energy for the next cycle (Fig. 1).

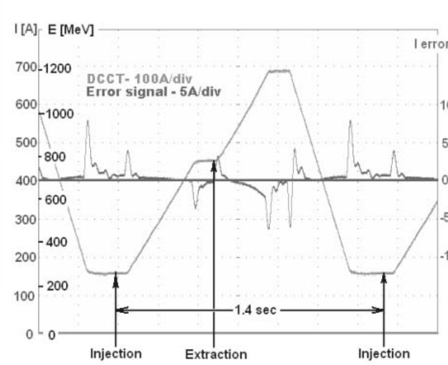

Figure 1: The ramping cycle, shown for the main power supply in terms of booster energy and magnet current, with injection at 273 MeV and extraction at 800 MeV.

The booster can also be set to stop at either the injection energy or at any energy within the operation range, at which point the machine can be tuned. All magnet controls are in terms of the physical units of the machine (i.e. orbit correctors in milliradians, quadrupole trims in m^{-2}, sextupoles in m^{-3}). When the booster stops ramping, all magnet control knobs are updated from the ramping waveform to reflect the set value for that particular energy, allowing for smooth tuning with stored beam. As the controls are tuned, a new waveform with new settings for all energies is created, based on the new value. This new waveform is in place for the next ramp cycle. The waveforms showing the array of values can be viewed in a two-dimensional plot (i.e. mrad setting of an orbit corrector versus booster energy).

Low Level Controls

The magnet power supplies all have an analog interface. The main power supply [5] powers the dipole magnets and the main coils in the quadrupole magnets (three types). Additional power supplies are used for quadrupole trims (16), sextupoles (4), and orbit trims (29). VMEbus waveform generators (Joerger Enterprises model VDACM) drive each of these power supplies.

Based on magnetic measurements and simulation, initial waveforms for each magnetic element were developed, with refinements made during commissioning. These are one-dimensional arrays of 1201 elements with the index corresponding to the booster energy (0–1200 MeV). These default arrays are included in compiled EPICS genSub routines.

At any time the booster is not ramping, any of the magnetic elements can be tuned with an analog output record. These analog output records function in two directions: at the end of a ramp, the records are written to by the underlying software with the appropriate value pulled from the current ramping waveform; then, the operator can tune the value, writing the new value back to the waveform. This allows for seamless, steady-state tuning of the booster. As the value is tuned, the new value, in terms of the effective focusing strength, is used for the present energy and for all higher energies in the ramping waveform. In this way, new ramping waveforms can be built up, from lower energy to higher energy, using stored beam to tune the ramp. Since these tuning values tend to be small, and the final magnet setting will be automatically normalized to energy, the actual ramping waveform in term of magnet current or field is reasonably smooth, even with the resulting stair-steps in the physics units waveform.

As the physics units waveform is re-written, the genSub routines add these new tuning values to the initial waveform arrays to build a new 1201 element array to describe the ramps for that element. The routine then builds an additional waveform, also of 1201 elements, using magnetic measurement data to map the power supply current required to produce the field for that particular magnet at the given energy (given by the index of the array). From the power supply current waveforms, an additional 1201 element waveform is generated representing the VDACM code describing the ramp which is then loaded to the waveform generators' memory for the ramp. The arrays in terms of effective focusing strength (physics units) and in terms of magnet power supply Amperes (Fig. 2) can be viewed or saved.

Using a different section of the waveform generators' memory, a waveform describing the ramp down from 1.2 GeV to injection energy (and from injection energy to zero for shutdown) is also recorded. These waveforms are the mirror image of the ramp up waveforms, but only have 601 elements (2 MeV per step). This ensures a smooth, repeatable normalization cycle for the booster magnets. The VDACMs are run at a fixed clock rate of 1.5625 kHz which

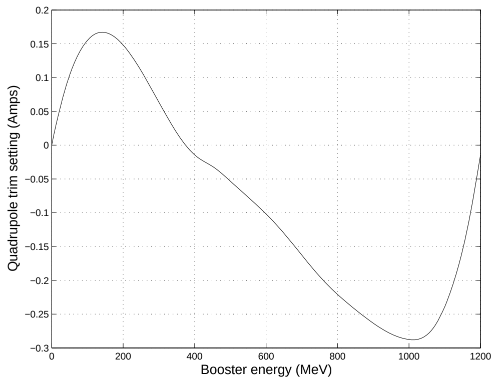

Figure 2: A defocusing quadrupole trim power supply current setting for the energy ramp cycle.

corresponds to a ramp up of 1.5625 GeV per second and a ramp down of 3.125 GeV per second. The timing system provides an external trigger to the VDACMs to synchronize the ramp. The length of the ramp is controlled by setting the number of clock ticks that the waveform generators run. Each tick corresponds to a 1 MeV change in energy so any energy can easily be selected. At the end of the ramp segment, the VDACM generates an interrupt. This interrupt is used to signal the timing system and to trigger the update of the operator interface with the present setting of each magnet element (both in terms of physics units for tuning and in terms of current for power supply monitoring) and the present setting of the booster's energy in MeV. No effort is made to track these set points during the ramp itself, although read backs monitor the power supply current continuously during the cycle.

COMMISSIONING

Several minor issues emerged during commissioning. However, the control system proved to be versatile enough to handle them with only minor modification.

During early booster commissioning, most of the tuning required was at injection energy. Instabilities in the linac injector resulted in changes in orbit for the incoming beam; the booster orbit required adjustment to be compatible with the orbit in the linac to booster transfer line. The initial strategy of propagating any changes in the booster ramping waveforms to all higher energies resulted in unintended orbit changes for the higher energies. The waveform tuning routines were modified to check if tuning was occurring at injection energy. If so, the change is not propagated to the higher energies. Instead it is propagated to the lower energies, to ensure a smooth curve for power supply startup and shutdown. This can result in a step to the power supply current at the first step of the energy ramp up from injection energy, but this has not been large enough to cause noticeable losses during the ramp.

The booster was designed with a vertical local orbit bump at the injection and extraction septa during injection and extraction. This bump allows for a single injection kicker and single extraction kicker. Initial designs called for this orbit bump to ramp to a zero orbit during the start of the energy ramp and then ramp back to the bumped orbit just before extraction. This resulted in separate routines to control this power supply differently from the energy ramping power supplies. However, during commissioning, we demonstrated that the bumped orbit did not cause significant beam loss during energy ramps up to at least 800 MeV. Currently, we are treating the bump power supply in the same manner as all of the other ramping power supplies, ramping it with a fixed bump with energy. At operations at the higher energies, it may be necessary to reduce the bump size during the energy ramp.

The flexibility of the control system and this ramping scheme was tested during commissioning. A fault in the injection linac resulted in the temporary bypass of one accelerating section. This resulted in a change of injection energy from 273 MeV to 242 MeV. After re-tuning the linac, the only change required for the linac to booster transfer line and for the booster was to change the injection energy setting to the new energy. Injection and ramping worked as before, with all magnet settings automatically rescaled for the new energy setting.

CONCLUSION

The ramping magnet controls have proven to be very versatile have and simplified initial commissioning and operation of the booster. Additional tuning is still required above 0.8 GeV, but up to that energy, the booster is already operating in a turn-key manner, with the system's nonlinearities hidden from the high level interface. As additional tuning occurs, information learned can easily be used to refine the low level ramping waveforms (as has already been done through one iteration). In this way, the controls adapt to operational needs, with all system specific issues compensated in the low level software.

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