CHALLENGES FOR ENERGY RAMPING IN A COMPACT BOOSTER SYNCHROTRON*

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Abstract

A booster synchrotron has been recently commissioned at Duke University FEL Laboratory as a part of the High Intensity Gamma-ray Source (HIGS) facility. The booster provides top-off injection into the storage ring in the energy range of 0.24 - 1.2 GeV. In order to minimize the cost of the project, the booster is designed with a very compact footprint. As a result, unconventionally high field bending magnets at 1.76 T are required. A main ramping power supply drives all dipoles and quadrupoles. Quadrupole trims are used to compensate for tune changes caused by the change of relative focusing strength during ramping. Sextupoles compensate for chromatic effects caused by dipole magnet pole saturation. All these compensations have to be performed as a function of beam energy. Above 1.1 GeV, where the magnets are heavily saturated, the reduction of dynamic aperture is compensated by redistribution of strength among the sextupole families. With these compensations, effects of the magnet saturation do not cause any considerable beam loss during injection, energy ramping, and extraction.

DUKE BOOSTER LATTICE

The Duke booster is a compact 31.9 m circumference synchrotron with race-track shape. Figure 1 shows the booster layout and lattice. Table 1 presents parameters of the booster. One of the primary concerns for the booster was fitting it into existing storage ring room in order to avoid cost extensive building construction. The compactness of the booster resulted in unconventionally high 1.76 T field in the bending dipoles at maximum energy of 1.2 GeV [1]. The saturation of the dipole poles at this field affects the lattice very considerably [2]. It appears to have particularly adverse impact in combination with a substantially non-zero beam orbit [3]. As a result, a number of special techniques compensating these undesirable effects have to be developed.

The beam is injected into the booster from a linac at energy of 0.24 – 0.27 GeV. The injection and extraction are vertical using identical horizontal Lamberson injection and extraction septum magnets. The beam vertical orbit is bumped for injection/extraction (see Figure 2). This bump, identical for injection and extraction, allows us to use a single injection and a single extraction kicker. The local bump in the septum magnets is produced by four strong vertical trims (TY on Figure 1) fed by the same power supply.

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The extraction energy of the booster varies from 0.24 to 1.2 GeV. The booster and the storage ring are fully synchronized for the extraction. The RF frequency of the booster may be tuned independently or be phase-locked to the master oscillator of the main ring [4]. The ratio of the harmonic numbers of the booster and ring of 19/64 provides for extraction of any individual electron bunch from the booster into any selected RF bucket of the storage ring. The short pulse of extraction kicker supports the extraction of individual bunches without disturbing others. The booster lattice has been specifically optimize to reduce the required kick and therefore to make the short pulse kicker feasible.

Table 1: Booster parameters

	Single bunch	Two bunches
Maximum beam energy [GeV]	1.2	
Injection energy [GeV]	0.24-0.27	
Stored beam current [mA]	1.5-2	2-4
Circumference [m]	31.902	
Bending radius [m]	2.273	
RF frequency [MHz]	178.55	
Harmonic number	19	
Nominal operation cycle [sec]	1.4-1.6	2.3-2.5
Energy rise time [sec]	0.59–0.61	
Maximum $\beta_x/\ \beta_y/\ \eta_x$ [m]	27.2/9.9/1.65	
Betatron tunes Q_x/Q_y	2.375/ 0.425	
Momentum compaction factor	0.158	
Natural chromaticity C_x/C_y	-1.7/ -3.7	
At injection energy E=0.24 GeV:		
Energy acceptance	1.5 - 2%	
Damping times $\tau_{x,y}/\ \tau_s$ [mS]	195 / 385	
At maximum energy E=1.2 GeV:		
Beam emittance ε_x, ε_y [nm·rad]	~440/ 6	
Damping times $\tau_{x,y}/\ \tau_s$ [mS]	3.16 / 1.60	
Energy loss per turn [KeV]	80.7	
Energy spread σ_E/E	$6.8{\cdot}10^{-4}$	

COMPENSATION OF MAGNET SATURATION EFFECTS

Correction of betatron Tune Shift

The nonlinear energy dependency of the bending angle of the dipoles and focusing strength of the quadrupoles causes a change of linear lattice during the energy ramp [2]. Figure 3 shows result of simulation of the betatron tunes drift on the ramp from 0.27 GeV to 1.2 GeV without dynamic tune correction. This simulation is based upon magnetic measurement data corrected to agree with the

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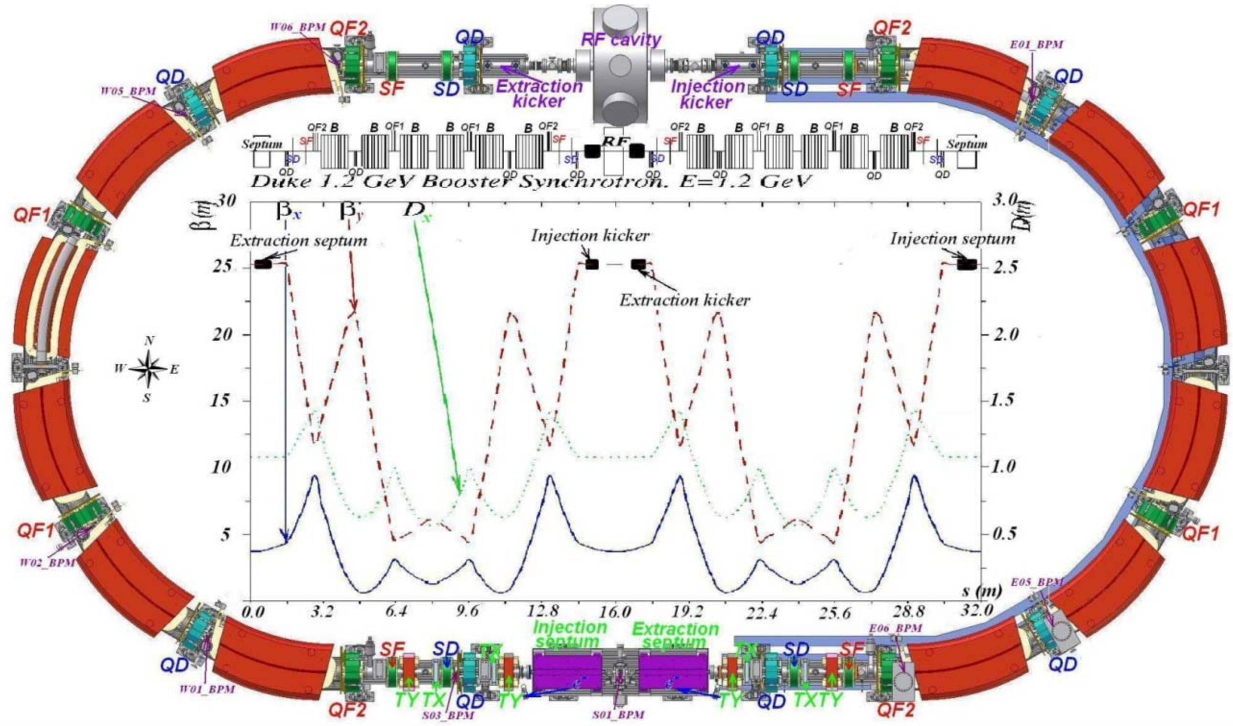

Figure 1: Layout and lattice of Duke booster synchrotron

real tune measurements at different energies. The lattice is pre-corrected at 0.27 GeV using quadrupole trims and correction currents are constant during the ramp. This γ-pattern is an interpretation of the nonlinearity of the booster magnets with energy (a booster "signature") in the tune space. Its down-coming wing results from the residual fields in the magnets, the up-coming one is caused by the magnet (mostly dipole) saturation. During commissioning of the energy ramp we clearly observed the beam vertical blow up around 0.85 GeV while crossing $4Qx+Qy=4$ differential resonance. The tune drift compensation is performed using the quadrupole trims in a feed forward scheme.

Correction of Chromaticity Shift

For the correction of chromaticity we use eight identical sextupoles (SF and SD in Figure 1) located in the straight sections. The pole of the bending dipole is shimmed so that the edge sextupole term is compensated by the body sextupole at E=0.5-0.8 GeV (see Figure 4). Due to the pole saturation, between 0.8 and 1.2 GeV, the body sextupole changes polarity and increases by a factor five. The contribution of the residual field also significantly changes the balance of the body and the edge sextupoles at E=0.27-0.5 GeV. Therefore, normalized settings of the sextupoles required to maintain positive chromaticity are very far from being constant. The optimal chromaticity is found around $C_{x/y}\approx0.8/1.5$ for injection (E=0.27 GeV) and $C_{x/y}\approx1.5/8.5$ for E=1.2 GeV. The transient chromaticity shift caused by the eddy currents in the vacuum chamber during the fast energy ramp is rather small and does not need to be corrected.

Correction of Coupling

The non-zero vertical orbit in the dipoles and in the sextupoles at injection and extraction leads to a substantial coupling of X and Y motion. To correct the coupling, we use the south straight section focusing sextupoles in which the vertical orbit at injection/extraction is fixed at $\Delta Y_{bump}\approx4.5$ mm. This enables us to produce the required skew quadrupole term as $\Delta K_{1skew}=K_2\cdot\Delta Y_{bump}$. To allow an independent correction of chromaticity and coupling, the sextupoles are divided into four individually controlled symmetrical families: north SF, south SF, north SD, and south SD.

Compensation of Extraction Septum Leak Fields

Due to non-ideal properties of magnetic material of the core, the magnetic field from the septum high field gap leaks out into the stored beam chamber. It directly results in the orbit distortion, tune and chromaticity shift, and change of coupling. These effects are particularly strong at injection energy with extraction septum set to extract at 1.0-1.2 GeV. They are measured and compensated as a function of the extraction energy, i.e. the extraction septum set current [4]. The orbit distortion is nearly eliminated by septum build-in horizontal and vertical trims, the betatron tune shift if corrected by the adjacent QD quads, chromaticity and the skew terms (i.e. coupling) are compensated by the adjacent south SD and south SF sextupoles accordingly. All these compensations are local and do not practically have any residual effects. The compensation is performed for a specific injection orbit, though it works reasonably well with some orbit variation.

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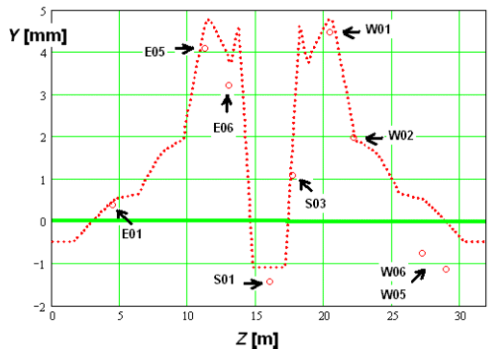

Figure 2: Injection and extraction vertical bump, simulations vs. measurements

Dynamic Aperture Limitations

The value of normalized sextupoles required for chromaticity and coupling compensation strongly affects dynamic aperture (DA). Initial simulations show that it is very beneficial for the DA to keep $K_{2SF} \approx K_{2SD}$. In this case their no-linear kicks are compensated to a large extent since the SF and SD sextupoles are paired locating very close by tune advance (see Figure 1). We used this advantage in the lattice and magnetic design, and it works well for nearly zero orbit at E=0.5-0.8 GeV. The residual field in the dipoles at lower energy and their saturation at higher energy totally destroy the balance of SD and SF.

We have also tried to avoid coupling at injection/extraction bumped orbit using for chromaticity compensation only north sextupoles, where orbit remains zero. However, in this scheme we observed strong reduction of DA at E>1.1 GeV. Dynamic simulations confirm a very significant difference for the symmetrical and asymmetrical scheme of chromaticity correction (Figure 5). On the other hand, with the fully symmetrical correction of chromaticity working well at nearly zero orbit, we have a large coupling at injection and extraction. That also dramatically reduces DA. We found a reasonable compromise between these two extremes, at $K_{2SFsouth}/K_{2SFnorth} \approx 2/1$. The plot shown in Figure 5 for this case remains practically the same for the non-bumped as well as for the bumped orbit.

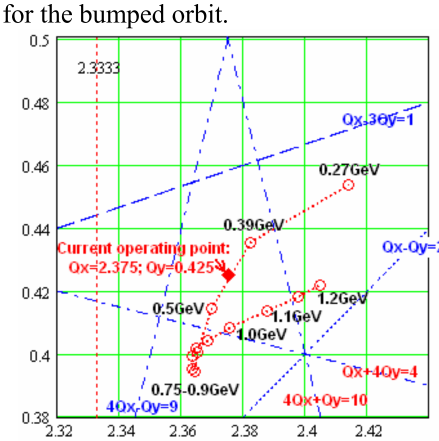

Figure 3: Tune diagram of the booster. The dotted red line is a "natural" drift of the betatron tunes during energy ramp 0.27-1.2 GeV without tune correction.

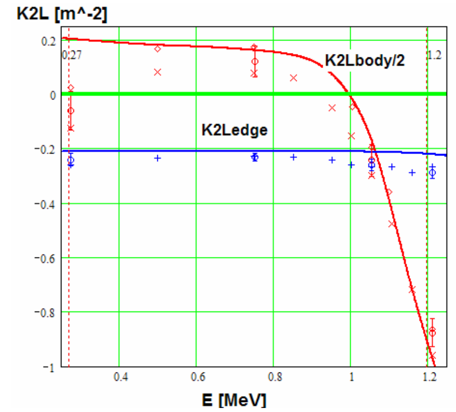

Figure 4: Integrated normalized sextupole in the bending dipole K2L=∫B″dl/Bρ, body and edge, simulations (solid lines) vs. measurements (symbols).

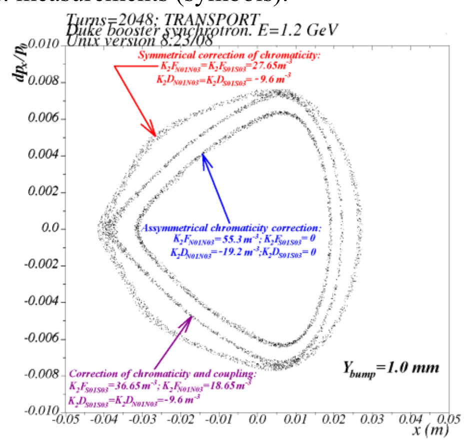

Figure 5: Survival plots (2048 turns) for different chromaticity and coupling compensation schemes. "Nearly" non-bumped orbit $\Delta Y_{max} \approx 1$ mm, at septa location (z=0), Δp/p=0.

CONCLUSION

With all the compensations implemented at low control level [6], effects of the magnet saturation do not cause any considerable beam loss during injection, energy ramping, and extraction. Similar compensations are imperative for any compact booster with a substantial saturation of the main magnets.

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