MULTIBUNCH INJECTION SCHEME FOR THE DUKE BOOSTER SYNCHROTRON FOR TOP-OFF INJECTION*

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Abstract

A booster-injector synchrotron has been recently built and commissioned at Duke University as a major part of the upgrade of the FEL and HIγS (Free Electron Laser and High Intensity γ-ray Source) facility. The booster provides for top-off injection into the FEL storage ring in the energy range of 0.18 - 1.2 GeV. The booster injection kicker was designed with a pulse length of about 100 ns, i.e. the length of 18 out of 19 booster RF separatrixes. This assumed a long train of electron bunches would be injected from the existing Duke FEL/HIγS linac. Such a scheme required a major linac upgrade from the existing single bunch photo emission mode to a multibunch thermionic mode. A big serious consequence of this change would be a much higher radiation levels in the linac tunnel and in the booster vault. Since commissioning, the booster was operating in either one or two bunch mode based upon single bunch injected from the linac. However, single bunch injection, with low charge from the linac, limits the capability of gamma production in loss mode operation, i.e. production of Compton gamma ray beams with the energy above 20-25 MeV. Upgrade of the linac for a higher repetition rate (up to 10 Hz) and modification of the injection kicker for 15-20 ns pulse length has allowed us to develop an alternative multibunch booster injection scheme and a significant increase of the injection rate into storage ring.

DUKE BOOSTER UPGRADES SINCE 2006

The Duke booster synchrotron is a compact 31.9 m circumference synchrotron with a race-track shape [1,2,3,4]. Figure 1 shows the booster layout and lattice. A linac with exit beam energy of up to 270 MeV is used as an injector into the booster. The linac consists of eleven standard SLAC sections fed by three klystrons. The electron gun operates in photo-injection mode. Since commissioning in 2006 and initial operation in 2007, the booster has seen a number of significant modifications.

The first modification was lowering of the injection energy from 270 MeV in 2006, down to 240 MeV in 2007, and then down to 180 MeV in 2008. The latter allowed us to set aside one modulator-klystron system as a spare. This modification increased reliability of linac operation and also considerably simplified the tuning of the linac. A lower injection energy required modification of the booster lattice for this energy. The booster energy acceptance had to be increased in order to cope with a larger energy spread and with much longer synchrotron damping (from 0.95 sec down to 0.28 sec). To increase the energy acceptance, the dispersion function was redistributed so that it was lower at the injection and extraction septa, i.e. at the most critical bottlenecks. Consequently, dispersion in the arcs, i.e. in the bending magnets, increased. This resulted in the growth of the synchrotron emmittance. However, at an injection energy of 180 MeV, the damped synchrotron emmittance was not an issue, as it was very small comparing to the initial phase space size of the beam injected from the linac. To accept most of the freshly injected beam before it was damped, and therefore to maximize the injection efficiency, the larger energy acceptance was most important. With the modified lattice, we managed to keep the injection efficiency from the linac into the booster at the level of 80-95%. The betatron tunes of the injection lattice were exactly the same as those of high energy

Table 1: Booster parameters

	# of bunches		
	1	2	6
Maximum beam energy [GeV]	1.2		
Injection energy [GeV]	0.18-0.27		
Stored beam current [mA]	1.5-2	2-4	10-12
Circumference [m]	31.902		
Bending radius [m]	2.273		
RF frequency [MHz]	178.55		
Harmonic number	19		
Nominal operation cycle [sec]	1.8-2.0	2.8-3.4	3.3-5.5
Injection rate into the Storage Ring [pC/sec]	50-90	50-120	200-350
Rate of replacement of electrons in the loss mode [10^9/sec]	0.3-0.6	0.3-0.8	1.2-2.2
Energy rise time [sec]	0.7		
Maximum β_x/ β_y/ η_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=0.18 GeV:			
Energy acceptance	2.0 - 2.5%		
Damping times $\tau_{x,y}$/ τ_s [ms]	0.94 / 0.47		
At maximum energy E=1.2 GeV:			
Beam emittance ε_x, ε_y [nm·rad]	~440/ 6		
Damping times $\tau_{x,y}$/ τ_s [ms]	3.16 / 1.60		
Energy loss per turn [KeV]	80.7		
Energy spread σ_E/E	$6.8\cdot10^{-4}$		

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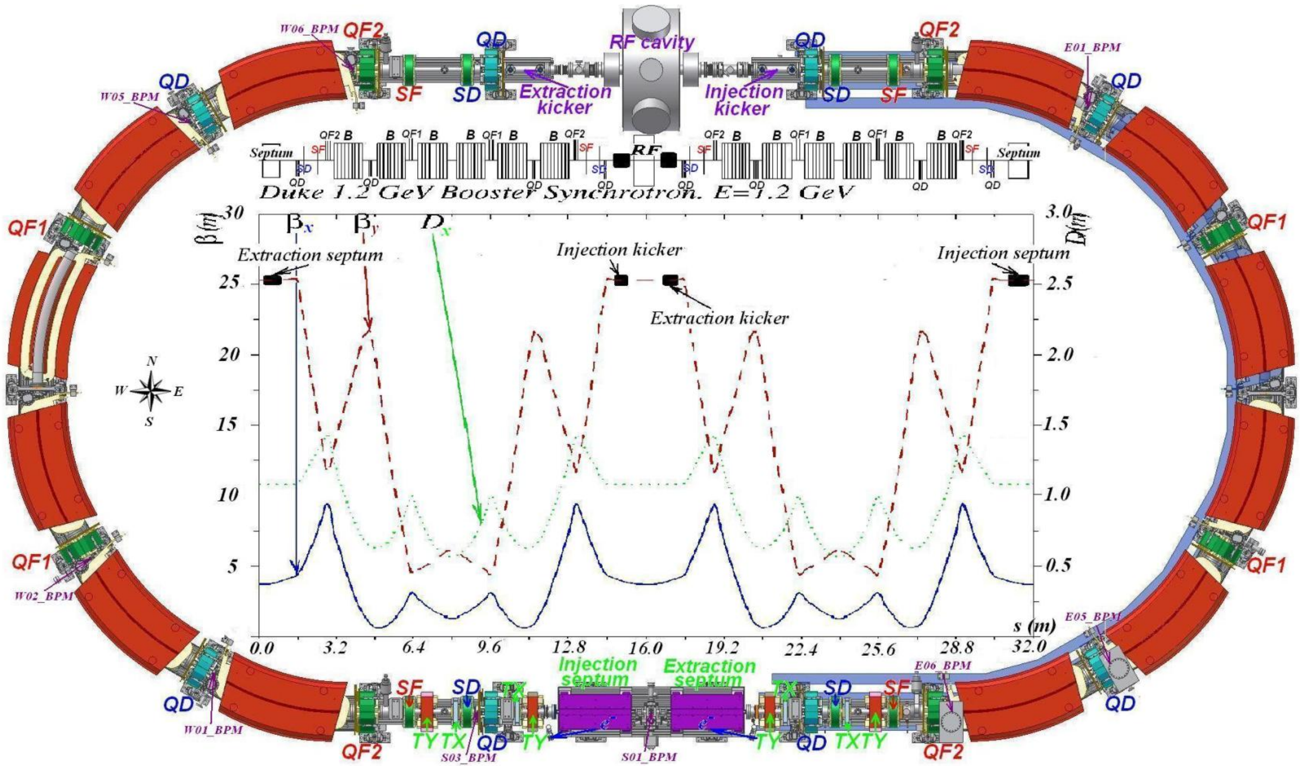

Figure 1: Mechanical layout and magnetic lattice of the Duke booster synchrotron.

(basic) lattice, which provided for a smooth transition between these two lattices during the energy ramp.

The second modification was development of the cost effective multi-bunch injection scheme. This upgrade is described in detail in the following section.

The parameters of the Duke Booster synchrotron with all upgrades fully accomplished are listed in Table 1. The efficiency of extraction from the booster into the storage ring is 60-90%. The range of the injection rates into the storage ring given in the Table 1 is based on realistic assumptions about variations in the quality of tuning of the linac, booster, transfer lines and storage ring.

The control system [6] and timing system [7] of the booster required no modification in hardware and software to accommodate all the upgrades.

MULTIBUNCH INJECTION SCHEME

The booster, designed for a single turn injection, was commissioned with single bunch injection [4]. Later we implemented a two-bunch injection mode using the circumstance that the width of the flat top of the injection kicker pulse was slightly less than the full booster revolution time (Figure 2). With two bunch mode we achieved about a 30% higher injection rate into the storage ring under the condition of a well tuned machine. Both single- and two-bunch injection with a low charge from the linac (less than 0.25 nC per pulse) limited the injection rate into the storage ring. It mostly affected the capability of gamma ray production in the loss mode operation at gamma energies above 20-25 MeV, with the storage ring was above 750-800 MeV. The development of the multi-bunch injection scheme allows us to raise the gamma production rate by a factor of 2-3, routinely replenishing up to about $2.0\text{-}2.5 \cdot 10^9$ electrons per second (see Table 1).

The original pulse width of injection kicker of ~105 ns (~100 ns of the flat top) was designed assuming the injection of a long train of bunches from the linac. Two conventional options were considered: (1) the use of thermionic injection, and (2) using a stretched optical pulse for the photo-injection mode. Thermionic mode would create much higher radiation levels in the linac tunnel and in the booster vault. Both options required considerable funding, shutdown of accelerators, and other significant efforts. The most cost effective solution was found in the modification of the injection kicker driver to produce a very short pulse (see Figure 2) combined with driving the linac at the existing maximum repetition rate.

Modification of the Injection Kicker Driver to the Short Pulse

In the ideal case, if the kicker pulse duration was less than 11.2 ns (i.e. two booster RF buckets), up to all 19 buckets could be filled. However, the minimum possible pulse length of injection kicker, being determined by rise time of the switching device (a cold cathode thyratron [8]), was ~15 nS. We also found an additional limitation associated with some oscillation overlapped with a bell shape pulse (Figure 2, red). At this moment, our understanding is that this oscillation is related to a degradation of the thyratron. Such a non-periodical oscillation is a result of some internal process in the switching of the thyratron, and it is not caused by any outside circuitry. The possible mechanisms of this degradation are described in detail in [8]. Due to this factor, we had to deal a realistic minimum effective length of the kicker pulse of ~20 nS. The maximum number of bunches which we could inject into the booster without a substantial loss was experimentally found to be six (Table 1).

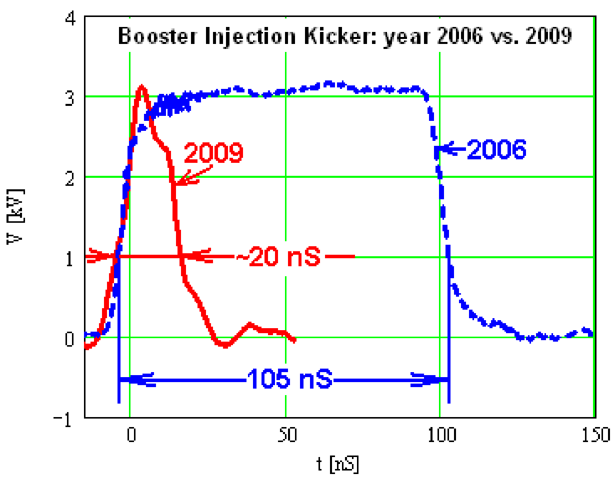

Figure 2: Injection kicker pulse before and after modification of the driver. Voltage per one electrode.

With a maximum booster beam current per bunch of about 2 mA (Table 1), as limited by the injection capability of the linac, we have not found any significant multi-bunch instabilities. Multi-bunch instabilities potentially could become a limitation at higher total injected charge.

This modification did not require any special shutdown of the accelerators and was accomplished during the regular maintenance hours.

Upgrade the Injection Linac for the High Repetition Rate

The maximum rate of injection into the storage ring in single-bunch or two-bunch modes was mostly limited (time-wise) by the booster ramping cycle. The repetition rate of the linac did not contribute significantly to the total operation cycle of the booster. When we used these 1-2 bunch modes, the linac rep rate was 0.7-1.0 Hz. In the multi-bunch injection mode as described above, the linac repetition rate becomes a major limitation. After the modification of the injection kicker driver, we boosted the linac repetition rate to 2 Hz. A higher linac injection rate of 5 to 10 Hz will require upgrading the RF modulators, in particular, the charging high voltage power supplies, with those capable of higher charging rates. The parameters given in Table 1 assume a repetition rate of the linac of 5 Hz. This upgrade is planned for the near future.

CONCLUSION

We have successfully developed a new multi-bunch injection scheme for the Duke booster synchrotron. With the planned linac upgrade to operate at 5 Hz, the booster will be able to deliver the required charge replacement rate of the storage ring operating the HIγS gamma-ray source in the loss mode at 10^9 γ/sec.

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