CHALLENGES FOR MAGNETIC DESIGN OF A COMPACT BOOSTER FED BY SINGLE POWER SUPPLY *

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Abstract

In design of full energy Booster injectors, commonly used in the modern accelerator facilities, there is a tendency of avoiding saturation of the magnetic elements in order to avoid losses associated with tune change during the energy ramp. Typical maximum field in the bending magnets of the modern Booster projects of 1.0-1.4 T results in the large circumference. For 0.27-1.2 GeV full energy Booster injector for the Duke FEL storage ring, recently under design and fabrication, there was an ultimate goal to fit it into existing storage ring room to avoid cost extensive building construction. Therefore, the Booster ring has to be compact, therefore the maximum field in the bending magnets was accepted 1.76 T. With a different level of saturation in the bending magnets, focusing and defocusing quadruples it was not possible to avoid a tune change with the energy rise. However, the ratio of saturation levels for the elements was optimized to avoid crossing of any significant resonance while ramping through the entire energy range. The lattice was simulated for different energies based on the results of 3D calculations of the magnetic elements with the use of MERMAID 3D code [1]. Another challenging part of the design was supplying all the dipoles and quadrupoles by single power supply.

BOOSTER LATTICE

A fast Booster-shynchrotron providing for a full energy top-off injection is commonly accepted in nowadays an integral part of any modern accelerator facility, specifically for SR facility. The one for the Duke FEL storage ring was proposed in the year 2000 as a part of the DOE proposal to improve drastically performance of the High Energy γ Source (HIγS) at Duke [2, 3].

The Booster will provide for top-off replacement of up 4 nC/sec of electron loss while producing intensive γ-rays beam of high energy. Extraction energy must be variable within 0.3-1.2 GeV range. Existing 270 MeV linac will be injector for the Booster. The RF frequencies of the Booster and the storage ring are identical. The odd ratio of the harmonic numbers of the ring and the Booster 64/19 provides for extraction of individual bunch from any bucket of the Booster into selected RF buckets of the storage ring. The lattice is optimized for the fast 11 nS pulse kicker providing for the single bunch extraction. The value of that kick has to be as low as possible. Thus, we have chosen vertical single kick symmetrical injection/extraction scheme with $\beta_y \approx 25$ m (Fig.2) at the location of the kickers and septum magnets. $Q_y \approx 1/2$ allows to install them in the opposite straight sections.

Table 1: Main parameters of the Booster (at 1.2 GeV)

Maximum beam energy [GeV]	1.2
Injection energy [GeV]	0.27
Average beam current [mA]	100
Circumference [m]	31.902
Bending radius [m]	2.273
RF frequency [MHz]	178.55
Number of bunches	8 - 19
Shortest operation cycle [sec]	2.5
Energy rise time, min [sec]	0.5 – 0.8
Beam emittance ε_x, ε_y [nm·rad]	350/ 15
Maximum β_x/ β_y/ η_x [m]	25.4/9.4/1.4
Betatron tunes Q_x/Q_y	2.43/ 0.46
Momentum compaction factor	0.153
Natural chromaticity C_x/C_y	-1.7/ -3.7
Damping times $\tau_{x,y}$/ τ_s [mS]	3.16 / 1.58
Energy loss per turn [KeV]	80.7
Energy spread $\sigma E/E$	$6.8 \cdot 10^{-4}$
<u>Magnetic System:</u>	
Dipoles (G=2.7 cm): ea./B_{max}[T]/L_{eff} [m]	12/ 1.76/ 1.19
Quadrupoles (D=5.0 cm):	
QF1: ea./ G_{max} [T/m]/ L_{eff} [m]	4/ 27.6/ 0.151
QF2: ea./ G_{max} [T/m]/ L_{eff} [m]	4/ 19.5/ 0.151
QD : ea./ G_{max} [T/m]/ L_{eff} [m]	8/ 8.4/ 0.131
Supplied by the same current I_{max} [A]	700
Sextupoles (D=6.0 cm):	
SF: ea./ B''_{max} [T/m^2]/ L_{eff} [m]	4/ 100/ 0.098
SD: ea./ B''_{max} [T/m^2]/ L_{eff} [m]	4/ 70 / 0.098

We have originally planned a single turn injection [4], though stacking is also considered. The orbit is pre-distorted prior to the kick by strong vertical trim dipoles located in the injection/extraction straight section and providing for 10 mm local orbit bump at septum magnets. The pre-distortion of the orbit relieves vertical aperture constrains associated with 27 mm dipole gap (~24 mm stay-clear). The kick value required for the injection/extraction is 0.675 mrad. The designed repetition rate for the extraction kicker is up to 25 Hz.

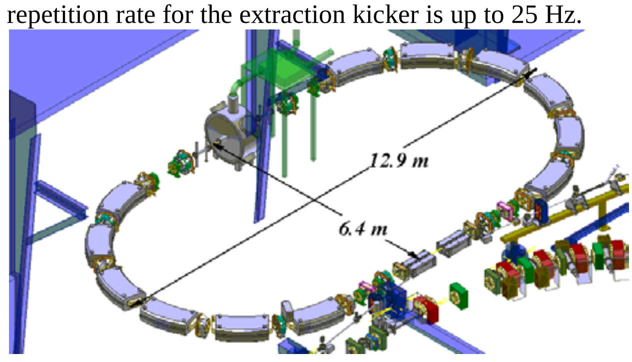

Figure 1: Layout of the Booster synchrotron in the North-East corner of the Duke FEL storage ring building.

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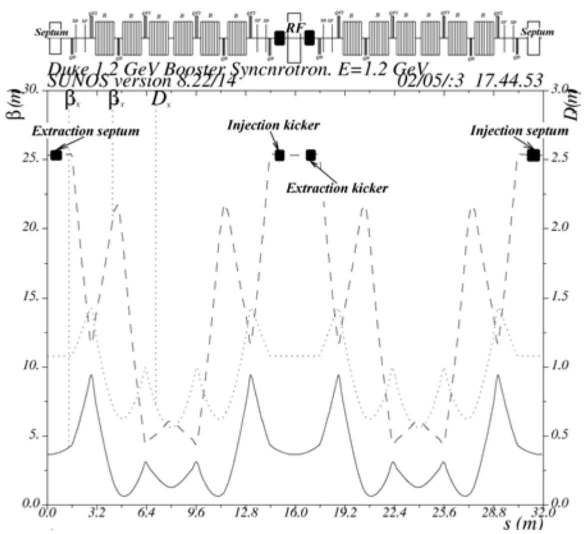

Figure 2: β-function and dispersion in the Booster ring.

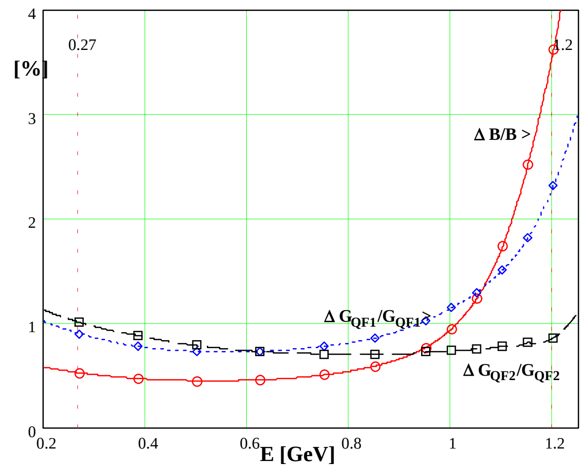

Figure 3: Effective "loss" of field/gradient in the core of the dipole and quadrupoles $\Delta B_{eff}/B$, $\Delta G_{eff}/G$ vs. energy.

MAGNETIC DESIGN

Use of single power supply for all magnets

To obtain required injection rate for the designed stored beam current the Booster must have 2.5 sec operation cycle. The energy has to ramp through the entire energy range 0.27-1.2 GeV within 0.5-0.8 sec. This is fast enough to consider supplying of all bending magnets and quads by the same power supply in order to avoid the current synchronization problems. Minimization of a variety of the quad families is a major concern in the lattice design of a ring fed by single power supply. In the Booster we use only two focusing and one defocusing families (see Table 1). Out of cost-saving and robustness consideration, the bending dipole has been constrained to be rectangular type. The required variety of the quad strengths is provided by combination of three types of coils and two types of iron cores. The coils have the same shape and different number of turns (10, 7 and 3 for QF1, QF2 and QD respectively). The cores are the same in cross section and different in length (146 mm for QF1, QF2 and 125 mm for QD).

All the dipoles and quads are laminated and have extensive end chamfers optimized both for the harmonic content and for the fast ramp [4, 5].

Cure of non-linearity of the magnets

The major cost-saving requirement of fitting the Booster into existing storage ring room (Fig.1) imposes strong limitation on its circumference and, therefore, on the bending radius of the dipoles. On the other hand, we tried to make possible an efficient full range energy ramp without any trimming, only by ramping the main current. From some level of the maximum field in the dipole in becomes simply impossible. The maximum of 1.76 T was found as a good compromise. The saturation of the poles at this field still significantly effects the lattice. Fig. 3 shows a relative effective "loss" of the field and gradient in the core of the dipole and quadrupole magnets due to the finite permeability of the iron. The effective "loss" is determined taking into account an additional saturation of the magnet edges. For example, for dipole it is $\Delta B/B=1-\int Bds/B_{\mu=\infty}\,L_{effinj}$, where $B_{\mu=\infty}$ is the field calculated for the infinite permeability of the iron and L_{effinj} is effective magnetic length at injection energy. Significant saturation effect in the dipole appears from B≈1.4 T which in our case corresponds to E=0.95 GeV. From that point the lattice starts rapidly changing. Fig.4 plots calculated drift of the betatron tunes on the energy ramp from 0.27 GeV to 1.2 GeV for all quads and bending magnets fed by the same current with no trims on. As one can see, the tune point makes a zigzag around a small spot at the beginning of the ramp and then, from the level of E=0.95 GeV, starts rapidly floating along a straight line. The change of the tunes directly results from different level of saturation of bending magnets, focusing and defocusing quads. Designing all the magnetic elements with the same level of is possible in principle but absolutely unpractical because of huge difference in their strength and effective length. However, the ratio of their saturation levels is optimized so that the tune change is reasonable and the tunes do not cross any significant resonance through the entire energy range. To find an optimum, we studied dependency of the tune change $\Delta Q_{x,y}$ on the effective saturation of the dipole and QF1 quad considering QF2 and QD practically linear. We observed that the total tune drift distance is approximately proportional to the non-linearity of the field loss in the dipole, while direction of the drift is determined by the ratio of effective saturation levels of the dipole and QF1 (Fig.5). The range $\Delta G_{QF1eff}/G_{QF1}$≈1.8–3.9 % was found relatively "safe". Thus, we accepted $\Delta G_{QF1eff}/G_{QF1=}$2.4 % for the QF1. This allows some safety margins for the uncertainty of the magnetic properties of the iron and its packing factor.

Though the Booster is designed with sufficient number and strength of trims in the magnets anyway [5], this approach relieves the requirements on the synchronization of the trim currents during the energy ramp.

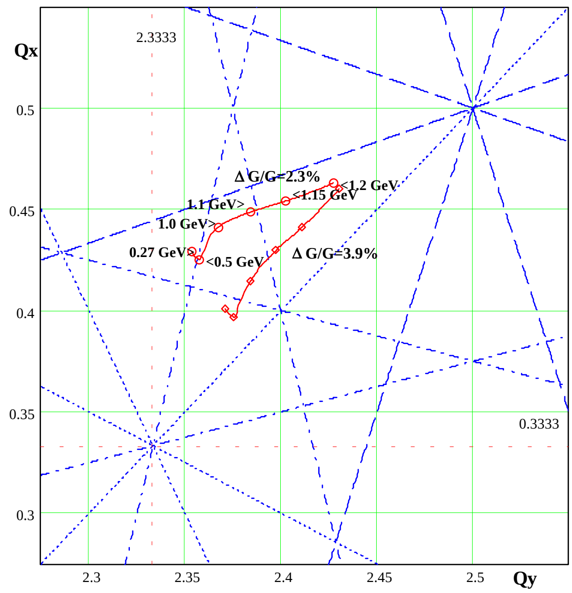

Figure 4: Drift of the betatron tunes during energy ramp 0.27-1.2 GeV with all the quads and bending magnets fed by the same current without trims. The upper curve (o) is for $\Delta G_{F1eff}/G_{F1}$=2.3 % and the lower curve (◊) for 3.9 %.

Compensation of chromaticity

Significant saturation of the dipole at the field higher than 1.4 T also causes nonlinear growth of sextupole component distributed along the dipole (body sextupole). Fig.6 shows dependency of the normalized integrated body sextupole along with the edge sextupole appearing at the ends of the dipole. This latter is almost constant over the entire range and determined by geometry of the dipole edge. Initial level of $K2L_{body}$ at low energy is pre-set by the pole shims to compensate $K2L_{edge}$ at injection. The growth of $K2L_{body}$ results in a growth of non-compensated chromaticity from C_x/C_y=-1.5/-3.8 at E=0.27 GeV to C_x/C_y=-6.4/+16.5 at E=1.2 GeV. The lattice is also optimized for favorable locations of the sextupoles

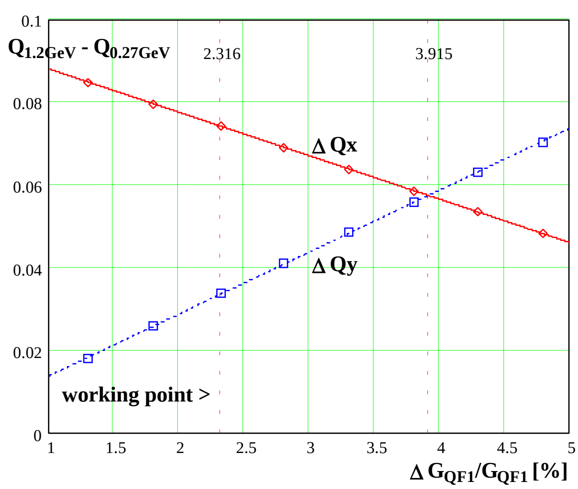

Figure 5: Tune change between E=0.27 GeV and 1.2 GeV for different effective level of saturation in the QF1 quad.

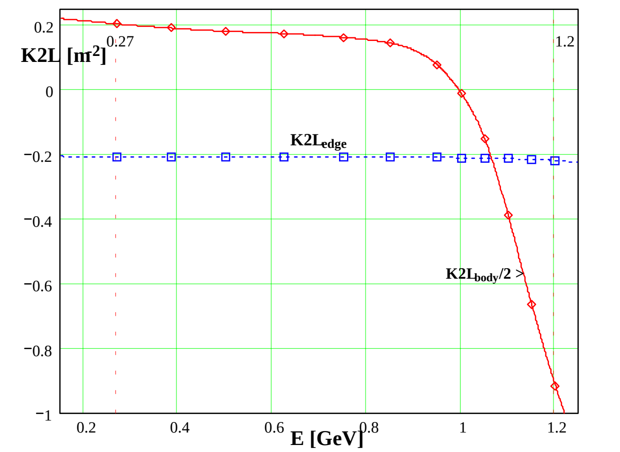

Figure 6: Integrated normalized sextupole in the bending dipole $K2L=\int B''dl/B\rho$ vs. energy. $K2L_{edge}$ is contribution of the fringe field and $K2L_{body}$ is body sextupole.

where they need a minimum strength to compensate chromaticity within entire energy range. This allows us to re-use existing solid yoke sextupoles to be driven only for 1/8 of their nominal strength. Sextupole component induced by the eddy currents in the vacuum chamber of the dipoles during a fast linear ramp shell be compensated by pre-setting the sextupoles to small constant levels.

CONCLUSIONS

We found that 1.75 T maximum field in the bending magnets is a reasonable compromise for a compact Booster without pre-determined use of the trims for the tune change compensation. Certainly, there are a number of uncertainties not allowing us to design a Booster on a paper without further corrections. Among those we have to mention magnetic properties of the iron, staking factor for the laminated core, their variation, random and systematic, from magnet to magnet, mechanical imperfection of assembly, residual fields, etc. Thus, the model of the Booster based upon the results of magnetic simulations shell be corrected after the fabrication and magnetic measurements of the real magnets.

REFERENCES

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