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Excitation curve calibration for the SSRF booster magnets and applications in the commissioning

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Abstract The Shanghai Synchrotron Radiation Facility (SSRF) is a low emittance third-generation synchrotron radiation light source under commissioning. The excitation curve calibration for the booster magnets is important to provide the magnet current configurations as reference. Calibration studies give the polynomial coefficients of each type of magnets and provide the magnet current configurations under different beam energies as beam is ramped at speed of 2 Hz. The applications of calibration in booster commissioning which show the accuracy of the magnetic excitation curve calibration are also discussed.

Key words Booster, Magnet, Calibration, Commissioning

CLC number TL5

1 Introduction

The SSRF booster accelerates 150 MeV electron beams from the linac to 3.5 GeV, before injecting them into the storage ring. The first 150 MeV beam was injected into the booster at 20:30 on September 30, 2007 and the multi-turn-accumulation signals were observed successfully 20 hours later[1].

Excitation curve calibration for the booster magnets is important for providing the suggested magnet current parameters under different working modes and different beam energies while the beam is ramped. In this paper, we report the procedures of the magnetic field measurement and calibration. Polynomial coefficients of each type of magnets and the magnet currents under different beam energies are given. Practices in applying the magnet excitation curve calibration to the booster commissioning are presented, too.

2 Magnetic excitation curve calibration

2.1 Magnet system of booster

The booster magnets include bending magnets (BEND), focusing and defocusing quadrupole magnets (QF and QD), sextupole magnets (SF and SD), and corrector magnets in horizontal and vertical planes (CH/CV)[2]. The designed parameters of the magnets are given in Table 1.

Table 1 Designed parameters of the booster magnets[2]

Type	No.	L_{eff} / m	Strength in AT Model
BEND	48	1.9	$\theta=\pi/24$ (rad)
QD	28	0.26	K=-1.475 (m^{-2})
QF	28	0.36	K=1.378 (m^{-2})
SD	22	0.1	S=-7.1100 (m^{-3})
SF	24	0.1	S=4.3128 (m^{-3})
CH/CV	28/28	0.1	–

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2.2 Magnetic field measurement

The time-consuming measurements on individual magnets include the magnet strength/current ratio as a transfer function of the excitation current, the degree of the magnetic field uniformity along the magnets of the same type, the multipole fields in BEND, etc[3].

Excitation curve calibration is based on the measurement data of the transfer functions. The integral field strengths $\int B dz$, $\int G dz$ and $\int S dz$ are measured in different currents and the transfer functions $\int B dz/I$, $\int G dz/I$ and $\int S dz/I$ are figured out respectively for BEND, quadrupole magnets (QUAD) and sextupole magnets(SEXT). $\int B dz$ and $\int B dz/I$ are measured for CH and CV.

The excitation currents of the same type of magnets usually differ from those of the other type of magnets in the measurement. The excitation currents of bending magnets start from 10 A to 980 A (restricted by the excitation power supply), and there are totally 98 measurements with a 10 A step. Details of excitation currents for other types of magnet are shown in Table 2.

The effective length of each type of magnets is also given out by magnetic field measurements as shown in Table 2. The measurement error of the effective magnetic length is about 2%.

Table 2 Excitation currents and measured effective length of each magnet type

Type	Excitation currents / A	Currents per step / A	L_{eff} / m
BEND	10~980	10	1.9344
QD	0~480	20	0.2780
QF	0~460	20	0.3764
SD	0~23	1	0.1169
SF	0~23	1	0.1169
CH/CV	1.34, 0.67, –0.67, –1.34	—	—*

* Not measured.

2.3 Excitation curve calibration

A procedural step in the machine operation is the conversion between the computer controlled digital setpoint of the magnets and the effective magnetic field acting on the beam traversing the magnets[4]. The conversion is divided into two steps:

(1) Digital setpoint to current I in Ampere,

(2) Current I to effective magnet strength (BL[T·m], G[T·m^{-1}], S[T·m^{-2}]).

In the first step, the Ampere/Digital ratio is characteristic of the power supply feeding a group of magnets and not the magnets themselves. In the second step, polynomials are fitted based on the measured data referred as

$$F = \sum_{i=0}^{n} P_i I^i \qquad (1)$$

The designed maximum field strength of BEND is 0.8045 T. The BEND work at linear region is shown in Fig.1a (n=3). Fitted polynomials vary a little with different orders. The differences of the fitted B-I excitation curve in orders between (n=6, 9, 12) and (n=3) are small as shown in Fig.1b.

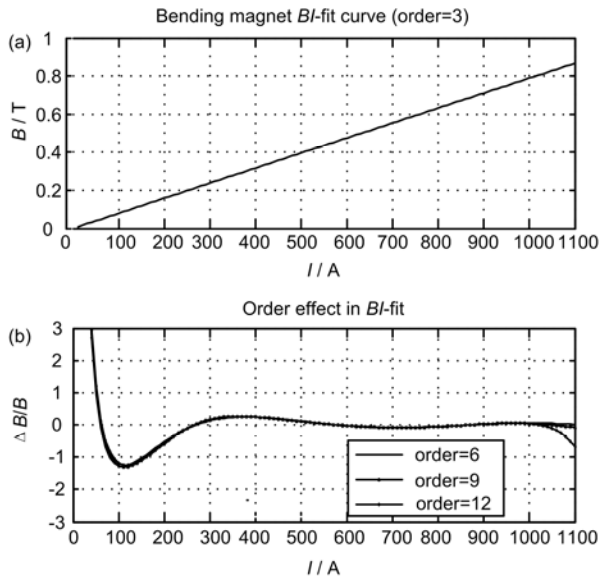

Fig.1 Fitted B-I curve of BEND (n=3) (a) and differences of fitted B-I curve in orders (b).

The selected orders were the same for BEND, QUAD and SEXT, i.e. n =3. For CH and CV, only linear behavior was assumed that the order n is selected as 1 and P_0 is set to 0. The function F is different for each type of the magnets:

for BEND,

$$\overline{BL}(I) = P_3 \times I^3 + P_2 \times I^2 + P_1 \times I + P_0 \quad (2)$$

for QUAD,

$$\overline{G}(I) = P_3 \times I^3 + P_2 \times I^2 + P_1 \times I + P_0 \quad (3)$$

for SEXT,

$$\overline{S}(I) = P_3 \times I^3 + P_2 \times I^2 + P_1 \times I + P_0 \quad (4)$$

and for CH and CV,

$$\overline{BL}(I) = P_1 \times I \quad (5)$$

As different types of the magnets (except CH and CV) are series-fed, the values of polynomial coefficients P of each type of the magnets are given in Table 3 by fitting the measured data based on Eqs.(2), (3), (4) and (5).

Table 3 Calibration coefficients of booster magnets

Type	P_3	P_2	P_1	P_0
BEND	-1.5420×10^{-11}	1.4049×10^{-8}	1.5262×10^{-3}	1.2784×10^{-3}
QD	-1.9918×10^{-9}	1.0784×10^{-6}	3.6300×10^{-2}	2.0020×10^{-2}
QF	-3.5479×10^{-8}	2.2328×10^{-6}	3.6195×10^{-2}	1.3582×10^{-2}
SD	-1.5503×10^{-4}	7.8200×10^{-3}	7.4572	1.0757
SF	-1.5783×10^{-4}	7.8425×10^{-3}	7.4705	1.0157
CH/CV	—	—	1.8451×10^{-3}	0

3 Application in commissioning

Matlab Middle Layer (MML) and Accelerator Toolbox (AT)[5] based on EPICS were used as the control software in the SSRF commissioning. The machine simulation and data processing can easily be executed by the conversion of magnet strengths, which can be easily switched between physics and hardware unit. And the entire Middle Layer is switched between simulator and online mode using the k2amp&amp2k function based on the magnet coefficient, which is determined by the calibration coefficients given in Table 3.

The designed I of each type of magnets under certain beam energy can be calculated.

(1) Transfer the physics strength from the AT model to the function F of Eq.(1), one obtains:

for BEND, CH and CV,

$$BL_{\text{eff}} = \theta\big|_{\text{AT}} \times B\rho \quad (6)$$

for QUAD,

$$G = K\big|_{\text{AT}} \times B\rho \quad (7)$$

and for SEXT,

$$S = 2 \times S\big|_{\text{AT}} \times B\rho \quad (8)$$

where $B\rho=10(E^2-E_0^2)^{1/2}/2.99792458$ is the magnetic rigidity that is determined by the beam energy, and $E_0= 0.51099906\times10^{-3}$ GeV.

(2) Calculate the current by using the fitted polynomial coefficients P by Eq.(1).

The booster accelerates 150 MeV electrons to 3.5 GeV. Therefore, the magnet currents need ramping with periodic alterations of the beam energy. The designed magnet currents at different beam energies, as the magnetic rigidity $B\rho$ changes with the beam energy, are listed in Table 4.

The booster was designed to work at the tune of [8.18, 5.23]. In its commissioning, after setting the magnet currents based on the calibrated currents in Table 4 at 158 MeV, in DC mode and with RF on, small beam was stored in booster (Fig.2), hence the tune of [8.46, 5.09].

As the real effective length of a magnet is not the same as the designed, the quadrupoles shall be rematched, i.e. the focus strength needs a change. So the magnet currents must be adjusted according to the measured effective length in both DC and ramping mode.

Table 4 Designed currents of magnets at different beam energies

Type	*I* / A			
BEND	42.06	44.35	857.01	1001.37
QD	19.77	20.85	404.84	472.99
QF	18.65	19.67	377.09	440.51
SD	0.81	0.86	18.71	21.83
SF	0.44	0.47	11.31	13.20
Energy / GeV	0.150	0.158*	3.0*	3.5

*In booster commissioning, energy of injected beam from the linac was 158 MeV, and firstly extraction beam energy to the storage ring was 3 GeV.

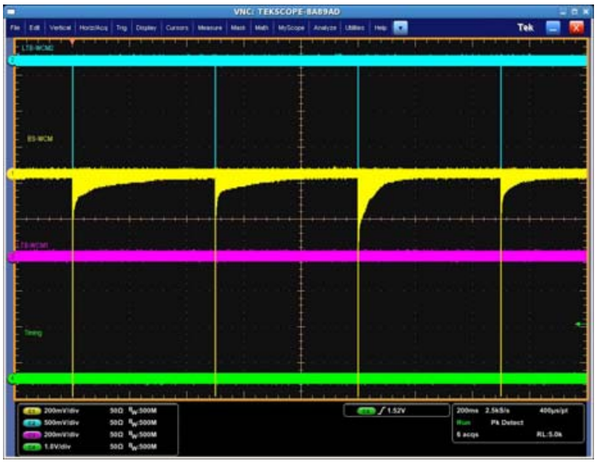

Fig.2 Designed beam at 158 MeV, [8.46, 5.09], 200 mV/div.

After adjusting the QD currents from 20.85 A to 20.25 A, QF currents from 19.67 A to 19.07 A, and SF currents from 0.47 A to 0.57 A, the stored beam increased markedly (Fig.3). The measured tune was [8.18, 5.40].

In ramping mode, probably because of the ramping power supply, the BEND currents were adjusted from 44.35 A to 46.10 A at 158 MeV and from 1001.37 A to 1040.9 A at 3.5 GeV. The QF currents (19.07 A at 158 MeV) were adjusted from 440.51 A to 437.14 A at 3.5 GeV. The QD currents (20.25 A at 158 MeV) were adjusted from 472.99 A to 458.22 A at 3.5 GeV. The SF currents (0.57 A at 158 MeV) were adjusted to 15.95 A at 3.5 GeV. The SD currents were 0.86A at 158 MeV and 21.83A at 3.5 GeV. The beam can be stored in ramping mode as shown in Fig.4. The excitation curve calibration was successfully applied in the commissioning.

Fig.3 Adjusted beam at 158 MeV, [8.18, 5.40], 200 mV/div.

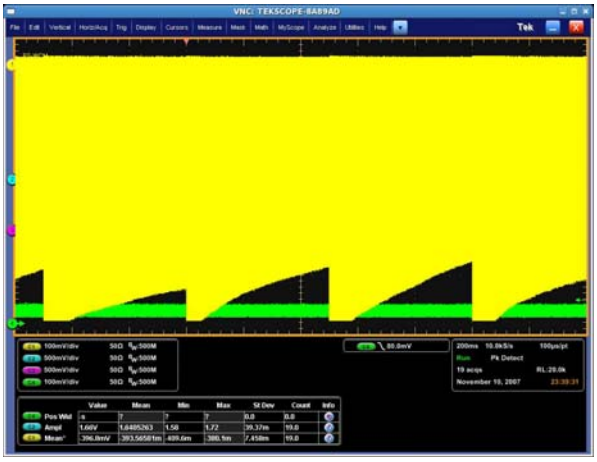

Fig.4 Beam in ramping mode, 100 mV/div.

The measured values of natural chromaticity, –10.08 and –7.84, are very close to the designed values of –9.91 (horizontal) and –7.45 (vertical). The measured values of corrected chromaticity are -0.5 (horizontal) and 0.2 (vertical). The magnetic excitation curve calibration is accurate for the sextupoles.

As the fitted polynomials of BEND and QUAD are rather linear, the currents of BEND and QUAD are usually adjusted linearly by simply multiplying a factor in commissioning.

4 Conclusions

Magnet excitation curve calibration had been successfully applied in the SSRF booster commissioning. The calibration coefficients can provide proper magnet current configurations for different working modes.

Because of the calibration inaccuracies and unavoidable installation and alignment errors, tiny adjustments of the magnet currents are usually needed. As the electron beam is affected with the KL when through the QUAD, the QUAD currents also need adjustment according to the measured magnet effective length which is usually different from the designed value.

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