

## COMMISSIONING OF SESAME BOOSTER

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### Abstract

Commissioning of the 800 MeV booster of SESAME light source started in December 2013. The 38.4 m circumference booster is a part of SESAME injector which includes also a 20 MeV classical microtron as a pre-injector that is in operation since 2012. The main results and experience obtained during the commissioning period are reported in this paper.

### INTRODUCTION

The 2.5 GeV SESAME storage ring will be filled with electron beam using the 800 MeV injector (composed of a 20 MeV classical microtron and a 800 MeV booster synchrotron) originally used in BESSY I [1]. After the injector has been commissioned [2] more improvements on booster performance have been recently achieved. This article spotlights the main booster commissioning results, the challenges faced, and reports our obtained experience. The booster ring is composed of 6 similar FODO cells containing 2 Bending Magnets (BM), 2 Focusing (QF), and one Defocusing (QD) Quadrupoles in each, with one Beam Position Monitor (BPM) and one Horizontal Corrector (HC) in each straight section but no vertical correctors. The main magnets are powered by 3 switch-mode power supplies from Bruker. The main booster parameters are listed in Table 1 and its design optics, with working point (2.22, 1.31) is shown in Fig. 1.

Table 1: Main parameters of SESAME booster.

Parameter	Symbol	Value
Inject / Extract energies (MeV)	$E_i / E_e$	20 / 800
Circumference (m)	C	38.4
Dipole bending radius (m)	$\rho$	2.67
Design tunes	$\nu_x, \nu_y$	2.22, 1.31
Emittance at top energy (nm.rad)	$\epsilon_0$	170
Design output current (mA)	I	5
Repetition rate (Hz)	$f_r$	1

The booster diagnostic system contains 4 15-cm strip-line and 2 button BPMs equipped with 6 Libera Electron units. The strip-line BPM 6 is switched also to a shaker mode for measuring tunes which are determined by FFT of the turn by turn BPM signal. It contains also a visible light diagnostic beamline, and 3 Aluminium Oxide Fluorescent Screens (FS) connected to analogue cameras

[3]. The screen FS1 is located at booster entrance next to injection septum, FS2 is located at one cell distance from FS1, and FS3 is located at the body of injection septum to serve as full turn beam detector. In addition to that there is a Bergoz Fast Current Transformer (FCT) with calibration factor 2.5 V/A, and a DC Current Transformer (DCCT) with calibration factor 0.5 V/mA [3].

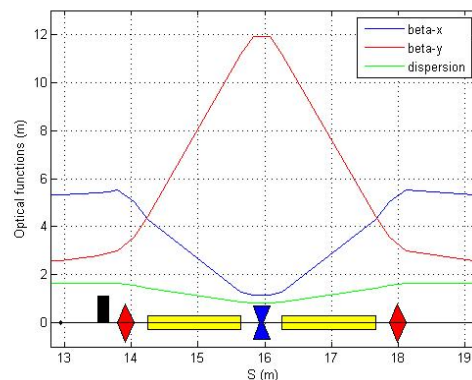


Figure 1: Optics of SESAME booster over one cell. The lattice structure shows BM (yellow), QF (red), QD (blue), HC (black rectangle) and BPM (black dot).

The 500 MHz RF system consists of a 2 kW solid state amplifier and a DORIS cavity with shunt impedance 3 MOhm. A gas pressure in the order  $10^{-8}$  mbar is achieved by seven 150 l/s ion pumps installed in the 6 straight sections and at body of the RF cavity. Beam injection into booster ring is done using a 100 kV/cm electrostatic septum which bends the incoming beam by 14.3 deg, and an injection kicker which produces a 4  $\mu$ s half-sine kick pulse with amplitude  $6 \times 10^{-4}$  T.m at 200 A, installed in the opposite section.

### BOOSTER COMMISSIONING

#### Beam First Few and Thousands of Turns

The 15-cm strip line BPMs (matched to 0.5 GHz) has almost zero sensitivity to the 3 GHz beam structure coming from microtron, which made tracking the first beam passage to be done only using the screens and FCT and tracking the beam for the first multi turns to be done using the FCT only. On the other hand, and due to the 2  $\mu$ s long injected beam whereas booster circumference is 0.128  $\mu$ s, it was not possible to differentiate the number of beam turns using the FCT. So the pulse length was reduced to around 0.3  $\mu$ s using microtron trim coils which made it possible to count the number of beam turns as shown in Fig. 2 (left) where the separation between two successive peaks is 0.128  $\mu$ s. When injection kicker was

off, the beam did 3 turns before getting lost at injection septum in agreement with simulations. By turning on the kicker, optimizing its timing and kick amplitude, and tuning quadrupole strengths around theoretical values, the beam did multi turns in booster, then thousands of turns by parallel tuning for dipoles and injection angle on July 17, 2014 as shown in Fig. 2 (right) with RF system off.

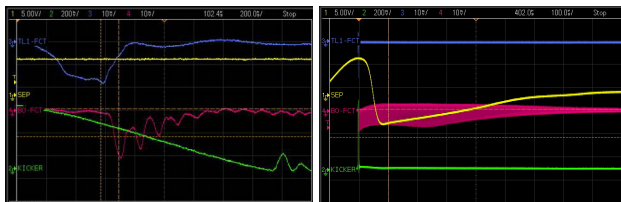


Figure 2: Many (left) and thousands (right) beam turns in booster ring as indicated by the FCT signal (pink). Injection septum kick (yellow), injection kicker kick (green) and coming beam in TL1 (blue) are shown.

This was achieved without orbit correction. However the beam current was substantially increased with some small orbit correction. The RF system was then turned on to have a stored beam.

### Characterizing the Booster DC Mode

The first thing to do after storing the beam was to measure the tunes. While the beam shaker was not available yet, horizontal tune was measured easily using the beam injection oscillations whereas to measure vertical tune the beam was injected with some vertical angle. Three working points have been defined through the search for stable working points; the documented design working point (2.22, 1.31) which had the lowest booster beam current and lifetime, the point (2.22, 1.4) and (2.28, 1.47) which had much higher beam current and lifetime ~ 100-150 ms. It is worth mentioning that theoretical calculations for beam lifetime give 150 ms at 20 MeV beam energy and average gas pressure in booster  $5 \times 10^{-7}$  mbar. The second working point was chosen for the booster operation. The measured booster optical functions are listed in Table 2 versus the theoretical ones.

Table 2: Measured versus theoretical optical functions.

Parameter	Measured	Theoretical
$\langle\beta_x\rangle, \langle\beta_y\rangle$ at QF (m)	4.8, 2.7	5.4, 3
$\langle\beta_x\rangle, \langle\beta_y\rangle$ at QD (m)	1, 10	1, 12.3
$\eta_x$ (m)	2	1.6

Average values of horizontal and vertical betatron functions,  $\langle\beta_x\rangle$  and  $\langle\beta_y\rangle$ , at quadrupoles have been deduced by measuring variation in tunes versus quadrupole strength using the known formula  $\langle\beta_{x,y}L_q\rangle = 4\pi\Delta v_{x,y} / (N\Delta k_q)$  with  $L, k, N$  are length, strength and number of quadrupoles in the same family. The dispersion function  $\eta_x$  was deduced by measuring

variation in beam orbit  $\Delta x$  versus RF frequency according to the relation  $\eta_x = -\alpha\Delta x / (\Delta f_{RF} / f_{RF})$ , using theoretical value of momentum compaction factor  $\alpha = 0.18$ .

### Ramping Booster Energy

Booster energy was ramped using tentative ramping curves for magnets and RF power. The measured average beam current at 800 MeV was  $< 1$  mA which was due to the big beam losses in the first few ms from injection. The beam losses were expected to be mainly due to beam loading effect and, to less extent, due to a small efficiency of RF capture to injected beam, and due to some destructive resonances mainly 4<sup>th</sup> order one. Efficiency of RF capture was optimized by investigating the starting RF cavity voltage at injection versus survived electron beam current in the booster in the DC RF mode. The highest capture efficiency was realised by using 5-6 kV as a starting voltage to the RF ramping curve which has a 70 kV peak voltage. The destructive resonances have been avoided over the ramping period by slightly modifying quadrupoles ramping curves. As a result the beam current was increased to 4 mA. Recently beam loading effect has been compensated by implementing RF Fast Feedback Loop (FFL) [4] which reduces the beam induced voltage in the cavity at the injection moment, something which increased the beam current to 7 mA as shown in Fig. 3. The fluctuation shown in booster beam current from injection to another is due to ripple in injection septum voltage that is still to be deeply investigated. Beam current values averaged over 100 injections before and after FFL implementation are 2.9 mA and 5.4 mA respectively. It should be noted that the 7 mA current in booster belongs to injection efficiency ~ 8% from microtron to booster.

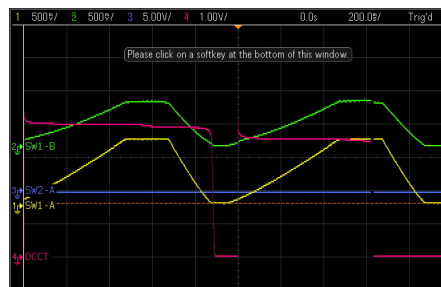


Figure 3: Booster beam current increased to 7 mA due to beam loading compensation. RF voltage (yellow), DCCT current (pink), and reflected RF power (green) are shown.

Characterization in the ramping mode has been done by measuring tunes and beam sizes over the 630 ms ramping period [3] in addition to chromaticities. For the tune measurement the beam has been excited by the strip-line shaker with 1-2 MHz bandwidth white noise around the expected tune frequency. Figure 4 shows the measured tunes before optimizing the quadrupoles ramping curves. Chromaticity was measured by changing RF frequency by  $\pm 50$  kHz and measuring the associated tunes. Chromaticity for a lattice without sextupoles should be the natural one, however ramping created eddy currents in vacuum

chamber in addition to dipole fringe field introduce sextupole components, hence contribute to chromaticity.

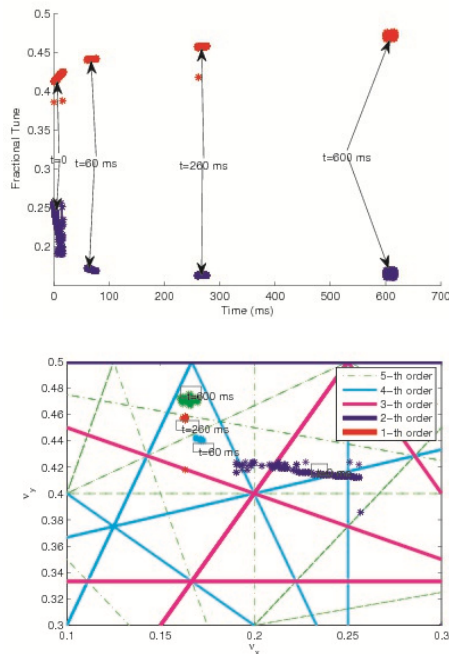


Figure 4: Measured tunes over booster energy ramping (top), and the corresponding path of the working point on the tune diagram (bottom).

The eddy current sextupole component has been analytically estimated [5]. For the sextupole component in the dipole, an integrated value of  $50 \text{ m}^{-3}$  dedicated from BESSY documentation has been used. Figure 5 shows the chromaticity measured over ramping period compared to theoretical one taking into account the eddy current and fringe field effects. The large discrepancy at the injection time is either due to error in estimating eddy current effect or in measurement or both.

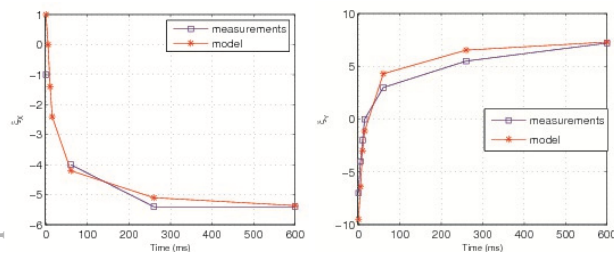


Figure 5: Measured horizontal (left) and vertical (right) chromaticities over ramping compared the theoretical one.

### Emittance Estimation

Booster emittance was deduced from beam size measurement, shown in Fig. 6, using the theoretical optical functions in Table 2 and energy spread  $4.2 \times 10^{-4}$ . The measured beam size 0.7 mm at 800 MeV deduced horizontal emittance 117 nm.rad, whereas theoretical one is 170 nm.rad as given by Elegant [6] and other codes.

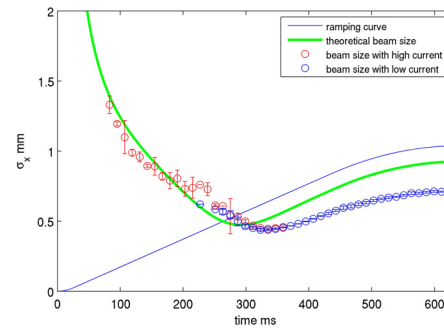


Figure 6: Measured versus theoretical rms beam size over booster energy ramping.

### Beam Extraction

Recently the 800 MeV electron beam has been extracted from the booster into the first part of booster-storage ring transfer line (TL2) which is installed for this purpose. Beam extraction is done by first moving the stored beam slowly close to the extraction septum sheet, positioned at  $x = 22 \text{ mm}$  from nominal orbit, by 3.5 ms full-sine kick of maximum amplitude  $1.3 \times 10^{-2} \text{ T.m}$  given by steerer magnet placed in the opposite section. Then while extraction septum is activated with 1 ms full-sine pulse of maximum amplitude 0.63 T.m, the beam is moved across its sheet by 190 ns rectangular kick from extraction kicker with rising time 40 ns. Figure 7 shows the extracted beam at Aluminium Oxide screen, striped into effective 5 by 3.5 mm<sup>2</sup> segments, installed downstream the exit of extraction septum.

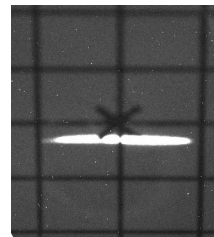


Figure 7: The 800 MeV extracted beam.

### CONCLUSION

SESAME booster has been commissioned and it is ready to inject into storage ring which still under installation. The booster commissioning was a valuable opportunity to have a good experience that can be used in the storage ring commissioning.

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