STATUS AND PROSPECTS OF THE BESSY II INJECTOR SYSTEM

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Abstract

The BESSY II injector system consists of a 50 MeV Linac, installed in preparation for TopUp operation, and a fast-ramping Booster synchrotron. The system provides injection efficiencies into the BESSY II Storage Ring well above 90 %. This contribution reports on the present status, measurements of energy acceptance as well as studies on coupled bunch-by-bunch instability. Requirements for BESSY VSR and possible upgrade scenarios are also discussed.

INJECTION PRINCIPLE

The injection system at BESSY II characterised 3rd generation light sources across the world. The scheme is over two decades old and has been one of the many successes at the facility. The injection stages shown in Fig. 1 starts deep within the labyrinth of the Storage Ring. Although the Microtron is still kept equipped in standby, the 50 MeV Linac [1] installed for the BESSY II TopUp mode has been in daily use since 2011. The 0.4 nC charged electron bunches leave the Linac and are transported along the long Injection Line into the Booster. This fast ramping synchrotron accelerates the bunches up to a final energy of 1.7 GeV and are extracted into the BESSY II Storage Ring.

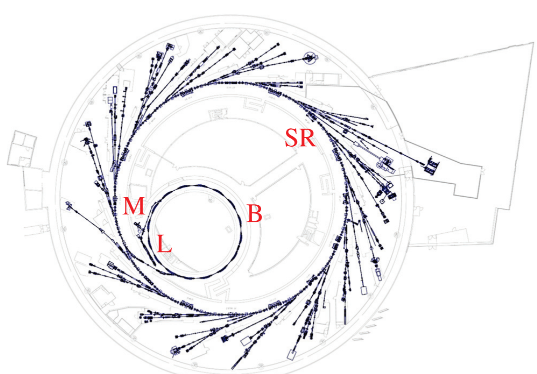

Figure 1: Engineering drawing of the BESSY II light source.

LINAC AND INJECTION LINE

The Linac commissioned in 2011, is capable of producing a 30x higher charge per bunch than the Microtron and has the advantage of more flexible bunch patterns. Todays standard user mode (Multi-Bunch Hybrid) shown in Fig. 2 is a amalgamation of the variety of users specifications [2]. It consists of a Hybrid (Chopper) bunch of 4 mA in the center of a 200 ns wide ion clearing gap, followed by a Pulse Picking by Resonant Excitation (PPRE) bunch for the single bunch science driven user community. Surrounding these is the standard multi-bunch mode each of 1 mA current separated by 2 ns. The remaining Slicing bunches deliver photons to the ultra-fast experiments at the Femtoslicing facility. The high purity and preservation of this standard fill pattern was only made possible by the Linac.

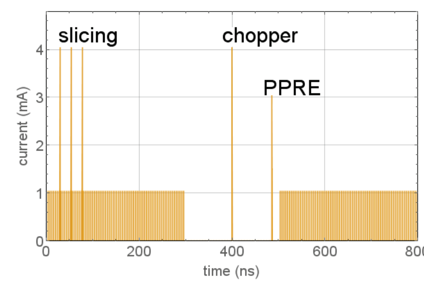

Figure 2: Flexible filling pattern for standard user operation.

The Injection Line which transports the electrons from the Linac to the Booster is sensitive to energy jitter produced by the Linac Klystron power supply, which lowers the injection rate. The singleturn injection technique, typical of 3rd generation facilities is via a Septum and a fast Kicker to deflect the beam onto the central orbit with a fall-off time of less than 100 ns. One, three or five bunches of similar charge are commonly accelerated in the Booster during TopUp depending on the fill pattern requirements.

BOOSTER SYNCHROTRON

White circuits triplets operating at a frequency of 10 Hz are used to independently power the 16 dipoles, focusing and defocussing quadrupoles. The magnetic lattice is based on a FODO structure with every second dipole missing. The tune was varied empirically over the last decade towards a low-emittance optic with optimised TopUp conditions. Within the Booster ramp the horizontal tune Fig. 3 varies only slightly on acceleration. The measurement is now fully automated, using dedicated diagnostic Kickers and a spectrum analyser. Two families of sextupoles were recommissioned in 2012 to correct the chromaticity due to eddy currents in the dipoles over the ramp and help suppress the high current single bunch Head-Tail instability. These additional higher order magnets have been found essential for routine operation.

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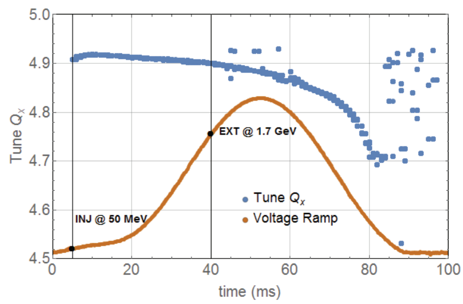

Figure 3: Horizontal tune over the 10 Hz Booster ramp. (for reference 5 ms injection, 40 ms extraction at 1.7 GeV)

INJECTION INTO THE STORAGE RING

To extract the beam from the Booster the closed orbit is bumped to the extraction pre-Septum, then a fast Kicker and main Septum are used to extract the beam. The Extraction Line transports the beam onwards to the Storage Ring. The closed orbit of the Storage Ring is shifted parallel to the Septum magnet by four Kickers. Typical single shot injection efficiencies of over 95 % are well within the radiation protection limits.

An alternative injection technique based on a non-linear kicker magnet [3] was realised in 2012. The essence of this scheme is a stand alone Kicker that deflects only the injected beam leaving the stored beam free to circulate without a bump. Although the scheme was successfully tested using a prototype magnet, the injection efficiencies in routine TopUp operation were unfortunately jeopardised. This prototype is still actively under investigation.

BESSY VSR

A global upgrade is the intermediate near future of BESSY II. Driving this modification onwards is the BESSY VSR project [4]. Here additional super conducting RF cavities will be installed into the Storage Ring to produce simultaneously long and short electron pulses. It is envisaged that the shorter bunches will have bunch lengths of 1.7 ps. A Technical Design Study (TDS) [5] and a complementary scientific case study were published in 2015.

The TDS highlights the technical challenges for BESSY II and the injector systems. The most prominent point with respect to the injector is the evidence that the bunch length on injection into the Storage Ring needs to be reduced from its existing value of 70 ps, in order to keep the high injection efficiencies. Presently the ratio of the bunch length of the Booster to Storage Ring is $\sigma_{\mathrm{SYN}}/\sigma_{\mathrm{SR}} \sim 7$. With BESSY VSR the ratio becomes even larger and the resulting energy spread after a quarter of a synchrotron period will be beyond the energy acceptance of the Storage Ring.

LONGITUDINAL ACCEPTANCE

BESSY II's timing systems allows one to actively measure the phase acceptance at each stage in the injection scheme. Fig. 4 shows the relative acceptance of the Booster. The temporal delay between the Linac and Booster was varied for a given Booster cavity voltage and the beam current in the Booster was measured.

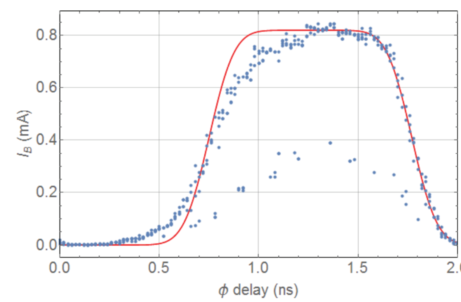

Figure 4: Current in Booster for varied injection phase.

In order to retrieve the energy acceptance from the red curve depicted in Fig. 4, an approximation that the fit is a convolution of a Gaussian and Flat-top distribution is assumed. The temporal acceptance τ_a = 800 ps, the synchrotron frequency f_s = 100 kHz at injection and the momentum compaction α_c = 0.033 (see red cross in Fig. 5a) can be substituted into Eq. (1) to estimate the energy acceptance of the Booster to be ±1%.

$$\delta = \frac{2\pi f_s \tau_a}{\alpha_c} \tag{1}$$

In a similar manner, the delay between the Booster and Storage Ring was varied for different cavity voltages to estimate the energy acceptance of the Storage Ring as ±3%. The results help characterise the upper boundary of the bunch length on extraction from the Booster for the BESSY VSR short bunches using particle tracking simulations, to be in the order of 20 ps. These findings confirm the original statement that the bunch length from the Booster needs to be shorter.

BOOSTER UPGRADE SCENARIOS

The upgrade towards producing a shorter bunch on injection into the Storage Ring could be one of the following three alternatives; shorter bunches from the present Linac, low alpha optic or the installation high gradient cavities in the Booster. Particle tracking simulations over the 10 Hz Booster ramp have shown the first suggestion to be irrelevant as quantum excitation in the Booster ramp dominates the beam dynamics. Shorter bunches from the Linac do not necessarily produce shorter bunches on extraction from the Booster.

The second suggestion, to modify the existing Booster optic towards low alpha is portrayed in Fig. 5. The figures show the flexibility in achieving low alpha optic at the cost of transversal beam degradation. The nominal Booster optic in Fig. 5a highlights the restrictions on the momentum compaction factor of a simple 16-fold symmetry FODO lattice and the red cross depicts the present setting.

Each blue point in Figs. 5a, 5b represents a randomly generated stable lattice and the chromatic invariant $\mathcal{H}$ value

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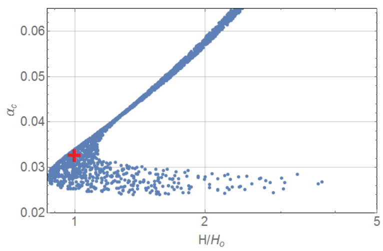
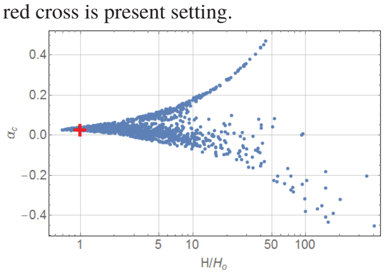


(a) Nominal FODO optic; QF QD $\alpha_c \nrightarrow 0$, red cross is present setting.



(b) Low alpha optic; 4 families Q1 Q2 Q3 Q4. $\alpha_c \to 0$ as $H/H_0 \to 2$

Figure 5: Towards low alpha optic in the Booster.

of the horizontal axis portrays transverse beam degradation (emittance equilibrium) relative to the nominal optic.

Fig. 5b shows that by installing independent quadrupole power supplies and creating four quadrupole families the 16-fold symmetry of the FODO lattice is broken allowing more optic tunability towards low alpha and hence shorter bunch lengths. Again, in the case of this fast ramping synchrotron, low alpha doesn't necessarily mean shorter bunches. Full start-to-end simulations have confirmed these improvements but as predicted they incur a growth in the transverse emittance. Before the investment of new quadrupole power supplies, fruitful alterations to the existing Booster lattice in order to break the symmetry and produce quasi-low alpha optic are foreseen.

The third suggestion to install additional high gradient cavities in the Booster is comprehensively described in the TDS. The recent upgrade to a solid state amplifier capable of 38 kW and 1 MV could produce a 30% decrease in the bunch length for the nominal optic. The general consensus is a combined low alpha and even higher gradient cavities upgrades utilizing the zero bunch length formula $\sigma_0 \sim \sqrt{|\alpha_c / V'|}$

DIAGNOSTICS

The diagnostics at BESSY II are continually improving [6]. The essential elements common in the Storage Ring are gradually been applied to the injection system. Notably the bunch current monitors (with redundancy) for TopUp are compared with those in the Booster. Turn-by-turn current measurements also exist in the Booster to aid the routine optimisation of the injection optic. Since 2013 the BESSY II Storage Ring has been equipped with digital bunch-by-bunch feedback (BBFB) systems. These systems are able to suppress both transverse and longitudinal beam instabilities over a wide range of machine parameters, while offering excellent diagnostic opportunities. The spare back-up BBFB unit was recently installed in the Booster to observe (without feedback) synchrotron oscillations such as those from Coupled Bunch Instabilities (CBI). Fig. 6 shows the longitudinal coordinate motion from the online diagnostics of one of the five bunches in the multi-bunch mode over the full 10 Hz cycle.

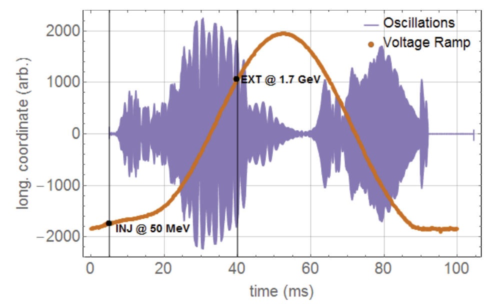


Figure 6: Longitudinal coupled bunch oscillations over the Booster cycle.

Although the bunch oscillations shown in Fig. 6 are considered to be longitudinally unstable, no beam loss occurs in the Booster during the energy ramp. At higher energies the electron bunch motion is damped due to excessive radiation. On extraction at approximately 40 ms the bunch is still unstable in this charge mode but does not hinder routine operation. One also observes the reappearance of the instability on the deceleration side of the ramp. In this particular setting the beam is lost at 90 ms. With the pending BESSY VSR project in mind, these instabilities will require active feedback to suppress the beam oscillations which lead to an effective bunch lengthening.

CONCLUSION

The installation of the Linac has helped improve the flexibility of the standard user fill pattern. The diagnostics of the Booster are continually improving to meet the high standards required for BESSY VSR. Possible upgrade scenarios have been discussed that may help to produce shorter bunches from the Booster in order to reach the TopUp injection efficiencies of BESSY VSR.

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