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# DEVELOPMENT OF NEW OPERATIONAL MODE FOR NSLS-II INJECTOR: LOW-ENERGY 100MeV LINAC-TO-BOOSTER INJECTION*

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*Abstract*

The NSLS-II injector consists of a 200 MeV linac and a 3 GeV full-energy booster synchrotron [1]. Optimization of the injector has continued since user operation started in October 2014. Beam losses have been minimized via injector tuning and stabilization. However, due to the recently increased frequency of klystrons arcing which shortens the lifetime of the klystrons, operation of the linac with lowered klystron output power would allow injection to be maintained with fewer trips and extended lifetime of klystrons. Besides, our ultimate goal is to prepare for the emergent operation with an injected energy of 100 MeV, which requires only a single klystron to power the linac, therefore permitting continuous operation while repairing other klystrons. A generic approach to the low energy operation of the injector, which is easily transferable to other light sources, has been implemented and experimentally demonstrated in the NSLS-II. It takes the full advantage of booster main magnet ramps current in operation via simply re-scaling them according to the new low injection energy. Once having the injected beam into the booster, beam based online optimization becomes essential to further improve booster injection and acceleration efficiencies. By doing so, most of early efforts for 200 MeV operation are still valid, and the number of changes to the injector and other part of the accelerator complex is also minimized. Several injection trials were carried out with scaled magnet settings of the linac, linac-to-booster (LtB) transport line, and the booster in a decremented approach with intermediate energies 170 MeV, 150 MeV, 130 MeV and 115 MeV. The 170 MeV beam from the linac was successfully injected into the booster on May 31, 2017 with a similar overall efficiency compared to the standard 200 MeV operation. Since then the 170 MeV operation has been adopted in NSLS-II user operation with less klystron trips therefore less interruptions to beamline users. 100MeV single-klystron operation has been successfully demonstrated with 20-30% overall efficiency, which is limited by the booster acceptance.

## INTRODUCTION

To meet user requirements on stability of average current (<1%), minimum time between injections (>1min), bunch-to-bunch variation of current (<20%), time to fill ring from zero to full charge (<5min), and reliability of the injection system, etc., the NSLS-II injector design employs a compact full-energy booster fed by a 200 MeV linac. The linac contains five traveling-wave S-band accelerating structures driven by two high-power klystrons. The booster has been designed to operate in the energy range of 170 MeV to 3 GeV [2]. Injection from the linac to the booster takes place at the energy of 200 MeV. The booster magnetic field and RF voltage are ramped in 400 ms to accelerate the electron beam from the injection energy to the nominal energy of 3 GeV. At the maximum field of the ramp, the electron beam is extracted from the booster and injected into the storage ring.

Optimization of the injector has continued since user operation started in October 2014, with less beam losses and an overall transfer efficiency (>70%). High level software has been developed to characterize the booster and injection parameters. However the original NSLS-II linac klystrons have shown frequent arcs in the tube which trips the klystron. These arcs shorten the lifetime of the klystrons. Therefore, operation of the linac with a lowered klystron output power would allow injection to be maintained with fewer trips and extended lifetime of those klystrons. We have initiated an R&D effort focused on enabling the lower energy injection into the booster for reducing the klystron power therefore reducing arcing. Furthermore, our ultimate goal is to get ready for the emergent operation with an injected energy of 100 MeV, which requires only a single klystron to power the linac, permitting continuous operation when a spare klystron is not available. The biggest challenge of this project is to learn how to control the orbit, tunes, and injected beam envelopes around the booster ring which is operating at energy below its design injection energy.

In this paper we investigate issues associated with the low energy injector operation and provide recipes for implementing reliable booster main magnet ramps which operate in the low injection energy starting from 100MeV up to 200 MeV. Once having the injected beam into the booster, beam based online optimization becomes essential for improving booster injection and acceleration efficiencies. Based on this generic method, a decremented approach with small step of intermediate energies 170 MeV, 150 MeV, 130 MeV and 115 MeV at the injection approves to be vital to the success of achieving the ultimate 100 MeV-injection.

## DESCRIPTION OF THE METHOD

We chose an approach which maintains the same booster extraction parameters and timing of the injection and extraction for both the low energy and nominal 200 MeV operations. This will minimize the number of changes to the injector and other part of the accelerator

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complex. All the settings, starting from the booster extraction to the storage ring injection including the booster-to-storage ring (BtS) transport line, stay the same.

The 170-MeV operation will be used as an example to describe the procedure on how to establish the low energy operation.

1. Scale the linac RF to 170 MeV.
2. Scale the LtB magnets to 170MeV.
3. Re-match LtB transport line for the new twiss parameters at the end of the linac.
4. Obtain unit conversions for all booster main magnets based on their field measurements. Then scale all the main magnet ramps (*dI*(*t*)/*dt*) according to the new injection energy (170MeV) while keeping booster extraction parameters the same with those in the nominal 200MeV operation (Eq.(1)); by doing so, those ramps for the 170 MeV injection are directly applicable to operation.

$$I_{Mag}(t) = I_{E_{inj}} + \int_{t_{inj}}^{t} \frac{dI_{E_{inj}}(t)}{dt} dt \qquad (1)$$

5. Scale the ramps of booster orbit correctors based on the 170MeV injection energy.
6. Scan and optimize RF amplitude and phase at the front porch via improving the injection efficiency and simultaneously minimizing the synchrotron oscillation.
7. Online optimize LtB steering magnets, injection magnets, booster sextupoles, and orbit correctors to improve booster injection and acceleration efficiencies.

Here $\frac{dI_{E_{inj}}(t)}{dt} = \frac{E_{3GeV}-E_{0.2GeV}}{E_{3GeV}-E_{inj}} \cdot \frac{dI_{0.2GeV}(t)}{dt}$, re-scale the 200 MeV ramp $\frac{dI_{0.2GeV}(t)}{dt}$ by the new low injection energy $E_{inj}$. $I_{E_{inj}}$ is the magnet setting at $E_{inj}$ based on unit conversion. Steps 1 to 4 and 7 are experimentally approved to be more important for the low energy operation of the injector, therefore they will be described in detail.

**Detail Description of Steps 1 to 3**:

The linac is powered by two klystrons. In the nominal 200 MeV operating, these klystrons operate at 33 MW and provide 100 MeV to the beam. The first klystron also powers the bunching cavity which captures and accelerates the beam from 90 keV to 4 MeV. The power in this cavity must remain approximately 16 MW to achieve a good transmission through the linac and maintain the bunch structure in spite of final different beam energies in the linac. The linac waveguide system provides the necessary flexibility to power this cavity with full power, while reducing the energy delivered by the klystron via shifting power from one cavity to another.

The power of the first klystron is reduced from 35 MW to 28 MW and the waveguide power distribution is rebalanced to provide 16 MW to the buncher cavity. The beam energy was checked to ensure it to be 85 MeV with only the first klystron being active. The second klystron is powered at 20 MW, and the final beam energy is measured to ensure it to be 170 MeV. The first klystron requires more power because of the longer waveguide and various power splitters and phase shifters which are necessary for this section of the linac.

The dipoles and majority of the quadrupoles in the LtB can be re-scaled to transport the linac beam to the booster. However, because of the energy change, twiss functions at the exit of linac are different. The LtB was designed such that five quadrupoles can be used to match the linac to the booster. Horizontal and vertical quadrupole scans are performed to measure twiss functions at the exit of the linac. ELEGANT is used to determine the settings of those five quadrupoles. LtB corrector magnets are tuned empirically to achieve good booster injection.

**Detail Description of Step 4**: Booster ramp generator There are two dipole families (BF and BD) and three quadrupole families (QF, QD, and QG) in the booster. Based on their magnetic field measurements, the unit conversion of power supply current in ampere (I(A)) and magnetic field in Tesla (B(T)) can be obtained via polynomial fitting of the data to the fourth order [Eq. (2)].

$$B(I) = K_0 + K_1 \cdot I + K_2 \cdot I^2 + K_3 \cdot I^3 + K_4 \cdot I^4 \qquad (2)$$

The power supply current at different injection energy can be obtained via the unit conversion of booster dipoles (right) and quadrupoles (left) (see Fig. 1).

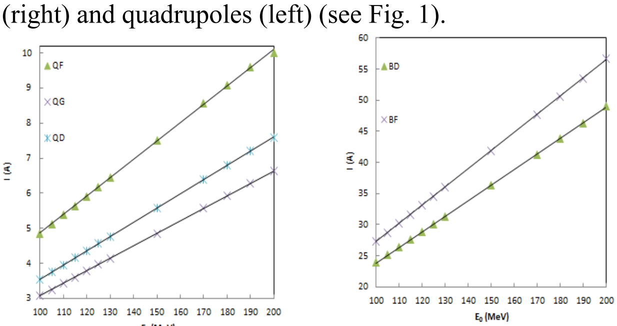


Figure 1: Booster dipole current of BD (green) and BF (black) at different injection energy (right); booster quadrupole current of QF (green), QD (cyan), and QG (black) at different injection energy (left).

Rescaling all booster ramps at 200 MeV based on injection settings at the new low energy, a complete set of booster ramps can be obtained. It was found experimentally that a low current hysteresis bump in-between 700 ms to 1000 ms in a cycle is essential for making the booster ramp repeatable. The function of generating such hysteresis bump is optimized based on different injection energy by always bringing the hysteresis bump down to zero current, which is the minimum current allowed by power supply. All these functions have been integrated into the booster ramp generator in matlab. It can run in a command line.

**Detail Description of Step 7**: Beam based online optimization.

The online optimization approach is based on use of the measured machine and beam parameters to evaluate the performance functions. Therefore, once the electron beam is established in the booster with a sufficient amount of

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time, such as several millisecond, beam based online optimization can be utilized to further improve booster injection and acceleration efficiencies.

A simple matlab script is implemented. The best candidate for the target function is the average current from 10 ms to 350 ms in the booster ramp, which is proportional to the product of booster injection and acceleration efficiencies. The most effective knobs are booster sextupoles and orbit correctors since booster dipoles are gradient magnets with significant sextupole components, which vary along the booster ramp and can be partially compensated by booster sextupoles. Online optimization provides model independent beam based tuning of booster sextupoles and orbit correctors. It was found experimentally that online optimization of booster sextupoles is essential for improving the booster acceleration efficiency.

## EXPERIMENTAL IMPLEMENTATION

Steps 1 to 5 in section 'Description of the Method' are important for establishing the injected beam into the booster with reasonable injection efficiency. We immediately obtained 10% booster injection efficiency after executing steps 1 through 5 in the 170 MeV injection case. The beam was lost about 10 ms after injection. Once having the injected beam into the booster, step 7 - beam based online optimization can be utilized for improving booster injection and acceleration efficiencies.

The average current of the first 10 ms after injection was used as the target function for online optimization. By optimizing sextupole settings, we were able to improve the acceleration efficiency to > 90% with survived beam all the way till the booster extraction. Afterwards, via re-matching the LtB to booster injection point and online optimizing booster orbit correctors with a modified target function, which is the average current from 10 ms to 350 ms covering nearly an entire booster cycle, we were able to further improve the booster injection efficiency > 90% while keeping the acceleration efficiency > 90%. By iterating between online optimizing booster sextupoles and correctors and re-matching the LtB to booster, we were able to establish the 170 MeV operation at high charge mode with the overall efficiency from the gun to the storage ring > 70%, which is similar to the nominal 200 MeV operation. This efficiency does not degrade in the high-charge 110 bunch mode. Since then, the 170 MeV operation has become the standard operational mode with less klystron trips therefore less frequent interruptions of the top-off injection.

By simply rescaling based on the optimized 170 MeV settings without any online optimization, we were able to reduce the booster injection energy down to 130 MeV still having 81% and 83% booster injection and acceleration efficiencies respectively

The next energy step was to 115 MeV. Once again we immediately obtained the injected beam all the way up to the extraction energy 3GeV, which provided an adequate target function to enable online optimization. Brief beam based online optimization via tuning booster sextupoles and orbit correctors and LtB steering magnets enhanced booster injection and acceleration efficiencies. Afterwards, the attempt to the 100 MeV injection was successful. 100MeV single-klystron operation has been successfully demonstrated with 20-30% overall efficiency, which is limited by booster acceptance.

As shown in Fig. 2, we gradually closed the energy slit in LtB transport line to reduce the energy spread of the beam. With the energy slit open at 3 mm, the beam energy spread is ~0.2%, both the injection and transmission efficiencies are about 100%.

Injection lattices at different low-energy operational modes have been characterized via ICA TBT based lattice tool recently developed in the NSLS-II [3]. As an example in the 100 MeV case, βx (top) and βy (bottom) are plotted as blue curves for the design and red curves for the measurement [Fig. 3].

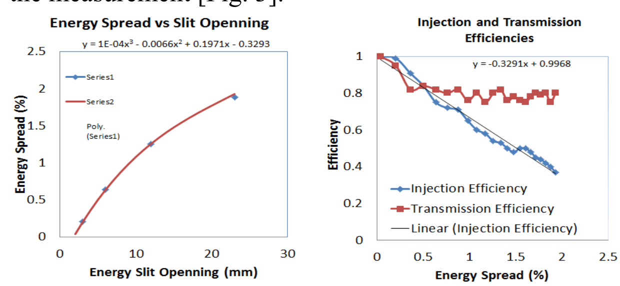


Figure 2: (left) Beam energy spread as a function of slit open aperture. (right) Booster injection (blue) and transmission (red) as a function of beam energy spread.

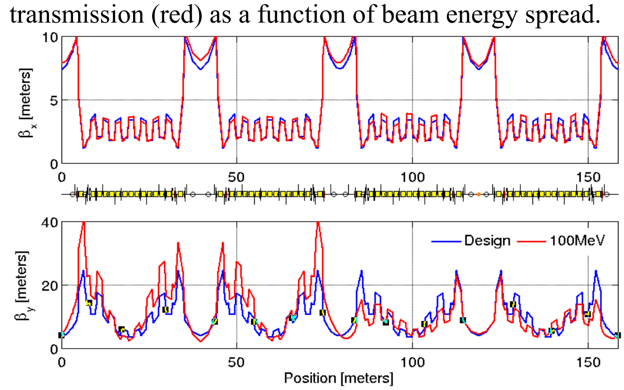


Figure 3: $\beta_x$ (top) and $\beta_y$ (bottom) are plotted as blue curves for the design and red curves for the measurement at the 100 MeV operation mode.

## CONCLUSION

A decremented approach with intermediate energies 170 MeV, 150 MeV, 130 MeV and 115 MeV takes advantages of pre-calculated low energy booster ramps, which are responsible for having the injected beam into the booster as an adequate target function for online optimization, and beam based online optimizations, which are responsible for improving booster injection and acceleration efficiencies. This generic approach approves to be vital for the success of achieving the ultimate 100 MeV-injection, and is applicable to other light sources in similar situations.

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