NSLS-II INJECTION CONCEPT

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Abstract

Currently the facility upgrade project is in progress at the NSLS (at Brookhaven National Laboratory). The goal of the NSLS-II is a 3 GeV ultra-low-emittance storage ring that will increase radiation brightness by three orders of magnitude over that of the present NSLS X-ray ring. The low emittance of the high brightness ring's lattice results in a short lifetime, so that a top-off injection mode becomes an operational necessity. Therefore, the NSLS-II injection system must provide, and efficiently inject, an electron beam at a high repetition rate.

In this paper, we present our concept of the NSLS-II injection system and discuss the conditions for, and constraints on, its design.

NSLS-II INJECTION REQUIREMENTS

A fuller description of the NSLS-II can be found in our other publications [1,2,3]. The project features a third-generation storage ring with optics based on 24 TBA cells. Table 1 lists the NSLS-II parameters relevant to the injection.

Table 1: Design parameters of NSLS-II

Energy	3 GeV
Operating current	500 mA
Circumference	~650m
RF frequency	500 MHz
Number of bunches	~700 out of ~1,000 buckets
Charge per bunch	1.55 nC
Estimated lifetime	3 hours (~6 hours with 3rd harmonic cavity[1])
Length of straight section	7 m
Injected beam emittance	<100 nm
Estimate of dynamic aperture necessary for injection	>±10mm (horizontal)

In the following, we discuss two options for the full-energy injector: a booster (repetition rate of a few Hz depending on the choice of a ramping power supply), or a linac (tens or hundreds of Hz).

The NSLS-II injection system must allow the storage ring to be filled rapidly. For the duration of the initial fill, we may write

$$\Delta t_{fill} = \frac{N_b \cdot \left(I_{inj} / I_b\right)}{f_{inj} \cdot N_m}, \tag{1}$$

where N_b is the number of bunches in the ring, I_{inj}/I_b is the ratio of current in the injected bunch to the nominal current in the storage ring bucket, f_{inj} is the repetition rate, and N_m is the number of bunches in the macropulse (for multi-bunch injection).

Using expression (1) and taking 3Hz and 60Hz for the repetition rate in the single-bunch mode, we obtain, respectively, 233 seconds (~4 min) and 11 seconds correspondingly. We note that we assumed lossless injection, and the ideal case "one injected bunch per bucket". This might be difficult to achieve; consequently, the initial fill can take longer, extending to tens of minutes for a low- repetition-rate injection system.

Between fills, the stored beam current decays to 50% of that at injection. These changes cause corresponding variations in the heat load that entail thermal drifts in the mechanical alignment of both the machine and the beamline's components.

This combination of the short lifetime with the high average current of the NSLS-II justifies implementing the top-off injection mode. This mode maintains the current and, therefore, the heat load, within a fraction of a percent, so eliminating the drifts and greatly stabilizing operations. Furthermore, the average luminosity of a light source approximately doubles by continually maintaining a maximum current. The use of the top-off injection mode is foreseen for many light sources, and already has been implemented in some (APS [4], SLS [5], SPRING-8 [6]).

Table 2 shows the specifications for top-off injection that satisfy users' requirements.

Table 2: Top-off injection parameters

Stability of average current	~0.5%
Time between injections in top-off	>1 min
Bunch-to-bunch variation of current	<20%

The first requirement follows from constancy of the heat load and already has been achieved in existing facilities. The second requirement is defined by the duration of user's experiments that are sensitive to the injection transients. The last requirement is somewhat arbitrary; however, experience with top-off injection at SLS demonstrates substantial intensity-correlated orbit oscillations for an uneven bunch pattern [7].

For the time interval between top-off cycles we get

$$\Delta t_{TO} = -\tau \cdot \ln\left(1 - \frac{\Delta I_b}{I_b}\right) \frac{N_m}{N_b} \Delta t_I \, f_{inj}, \tag{2}$$

where τ is the lifetime, $\Delta I_b/I_b$ is the bunch-to-bunch variation of current in the pattern, and Δt_I is the time interval for a single top-off cycle. To assess the stability of the ring's average current we can write

$$\Delta I_{SR} / I_{SR} \approx \Delta t_{TO} / \tau, \tag{3}$$

Using (2), we obtain the duration of the top-off cycle, Δt_I , equal to 6 seconds for a repetition rate of 3Hz, and 1 minute for the interval between the top-off cycles (Table 2). We note that this value is unacceptably large,

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[1] Estimate is based on the measured data from the SLS [8].

signifying that 10% of the overall beam time is spent on injection.

A system with a higher repetition rate of injection eliminates this problem. For example, for the repetition rate of 60 Hz, the duration of a single top-off cycle is only 300 ms (0.5% of beam time). On the other hand, this is equivalent to injecting 20 bunches during every top-off cycle (multi-bunch injection at 3 Hz). Here, however, the uneven distribution of charge in the macropulse may cause the bunch pattern in the ring to deteriorate while in the top-off mode. We are exploring this effect using simulations and experimental data.

INJECTION EFFICIENCY

The quality of the injected beam may play an important role in the efficiency of transport and injection that, in turn, affect the radiation environment in the machine. We have begun to study the injection efficiency by tracking particles through the existing NSLS-II lattice for a few turns. A description of the injection bump and the fast magnets is given in [11].

Figure 1 illustrates results of the tracking in horizontal phase space where the injected beam's emittance was 10- and 100-nm. As shown, the injected beam with the larger emittance exhibits betatron oscillations at larger amplitude; most likely, a fraction of particles located at the tails of oscillating beam eventually will be lost.

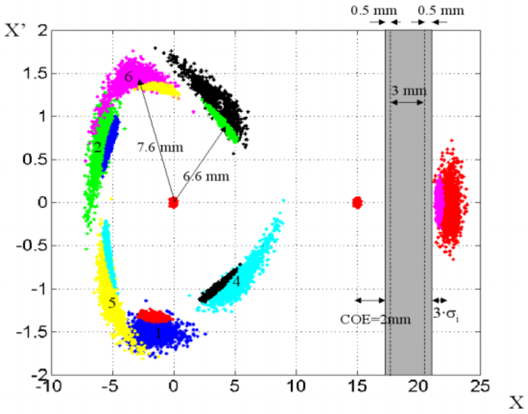

Figure 1: Particle tracking in phase space (mm, mrad) for the injected and stored beams. The shaded area corresponds to the size and location of the septum "knife". Tracking for the two emittances (10- and 100-nm) of the injected beam is plotted.

Presently, we are optimizing the injection efficiency with respect to the beam's emittance. We note that, in general, a small emittance (10 nm or less) of the injected beam result in better injection efficiency. From Fig. 1 we also estimate that the dynamic aperture needed for injection should be at least ~20 mm horizontally.

NSLS-II INJECTOR

The arguments discussed above led us to consider two possible solutions for the NSLS injector: a linac, and a booster. Looking for most efficient and cost-effective solution we compared both options in terms of the time format and parameters of the output beam, project and operational cost, power consumption, and potential for future upgrades. Below, we briefly describe both projects.

Linac

A linac is a key part of any injection system. Historically, linacs have been used to accelerate the beam to a minimal energy, sufficient for injection into a booster. This approach was motivated mainly by the high cost of the linac components. However, with the maturity of linac technology and commercial availability of klystrons, modulators, linac tanks and SLED cavities the cost of a linac has become comparable to a booster ring.

Today several new machines are using either existing or new linacs for full energy injection into storage rings. Examples include the KEK B-factory, Spring-8, SLAC B-factory and Pohang Light Source.

An added attraction of a linac is the low emittance, which eases injection tolerances into the ring, and more importantly provides a path for future upgrades towards next generation light sources [9, 10].

We analysed different options for the NSLS-2 linac-injector considering super- and normal-conducting RF structures. Our current design is based on 3 GHz normal-conducting RF sections (Table 3). The choice of frequency is motivated by the availability and cost of accelerating sections; furthermore, this value of the frequency is a harmonic of the storage ring RF.

In our design, we utilize the SLED scheme with 2 cavities fed by a single klystron. To increase reliability, we consider including 2 redundant SLED sections so bringing the maximum energy up to 3.4 GeV.

Table 3: Full-energy linac parameters

Overall length	~200 m
RF frequency	3 GHz
Accelerating gradient	20 MV/m
Repetition rate	60 Hz
Number of RF sections	17x2
Klystron power	45 MW
Hor./vert. emittance (3 GeV)	0.5 nm
Energy spread (3 GeV)	<0.1%
Bunch length	0.1-50 ps
Average power consumption	1 MW

Its high repetition rate and excellent beam quality make the linac an attractive candidate for the NSLS-2 injector. Being a single-pass accelerator, the linac-injector is flexible in performance and, due to pulsed mode of operation, has low power consumption and operational cost. Figure 2 depicts the layout of the full-energy linac facility.

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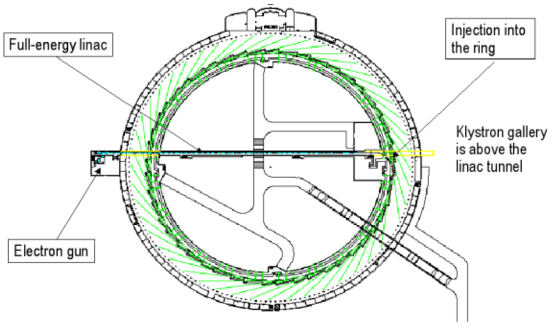

Figure 2: Layout of the full-energy linac.

Booster

To compare efficiency and cost of the linac we are developing a full-energy booster model. Table 4 summarizes its main parameters.

Table 4: Full-energy booster parameters

Injection energy	0.1 GeV
Circumference	170 m
Repetition rate	3 Hz
Horizontal emittance (3 GeV)	10.5 nm
Energy spread (3 GeV)	0.1%
RF Voltage	1.5 MV
RF acceptance	1%
Bunch length, rms (3 GeV)	39 ps
Average power consumption	0.7 MW

To ensure a small footprint and find a cost-effective solution, we designed the booster lattice out of 24 TME (theoretical minimum emittance) cells with gradient dipoles and two straight sections for injection and extraction (Fig. 4).

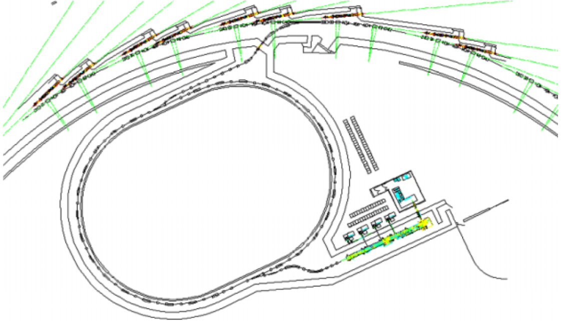

Figure 3: Full-energy booster layout.

During the design we estimated various aspects of the booster, such as its dynamic aperture, magnetic design of the gradient dipoles, and the effects of Eddy currents. The chosen booster lattice, based on gradient TME cells is feasible for creating a compact low-emittance solution. The booster project is fully described in [12].

Gun

The NSLS-II gun must deliver about 0.25 nC of charge per bunch in single- or multi-bunch mode of top-off operation. For the initial fill it is desirable to have more than 1.5 nC per pulse. It seems feasible to achieve these parameters in either a thermionic planar triode gun or photocathode rf gun; more detailed analysis is in progress.

CONCLUSION

The goal parameters of the NSLS-2 require developing a flexible and highly efficient injection system with high repetition rate. For the moment, we are investigating the potential of two options for the full-energy injector: a booster or a linear accelerator. Our preliminary analysis favors the possibility of designing a full-energy linac with parameters suitable for the effective operation of the 3rd generation storage ring. The linac's excellent beam quality, together with a high repetition rate makes it an attractive candidate as the NSLS-II injector. The short bunch length and low emittance of the linac beam offer the potential for future upgrades.

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