DESIGN CONSIDERATIONS OF THE NSLS-II INJECTION LINAC *

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Abstract

The NSLS-II injector system consists of a 3 GeV booster injected by a 200 MeV linac. Specifications of the linac are derived from Booster and Storage ring beam requirements. Linac design considerations are presented to meet these specifications.

INTRODUCTION

The NSLS-II is a proposed third generation light source at Brookhaven with sub nm-rad emittance to achieve 1nm photon beam resolution The design approach to achieve the requisite electron beam parameters is to use damping wigglers combined with soft (ρ=25m) dipole bends to reduce the bare lattice emittance of 2nm-rad to the required 0.5nm-rad [1] The resulting machine design has beam lifetime of ~2 hours dominated by Touschek scattering with significant contributions from the non-linear dynamics of the lattice and the 5mm vertical aperture of the small gap undulators.. To mitigate this short lifetime a third harmonic Landau cavity for stretching bunches longitudinally to increase the lifetime to ≥3 hours is proposed. To achieve stability in the electron beam orbit as well as photon beam optics top-off injection is required to keep thermal transients to a minimum. The NSLS-II injection linac is an S-band pulsed linac that will inject into a full energy booster that will in turn provide top-off injection into the NSLS-II. Storage ring top-off requirements are detailed followed by the design considerations for the linac to meet these requirements.

TOP-OFF REQUIREMENTS

Top-off injection has the dual purpose of doubling the average flux of a light source and eliminating the thermal transients associated with the decay of the stored beam between injections. To meet the beam stability requirements of the electron beam and photon optics the beam current must be kept constant to within 0.5%. Since the injection process requires the stored beam to be bumped toward the injection septum and the bumps are not entirely closed within the injection straight user experiments must have blanking enabled during injection transients. This results in a desire to minimize the number of injections, translating in a high charge per injection to maintain constant current in the ring. General user specifications for the NSLS-II injection in top-off mode are summarized in the Table 1.

Table 1: User specifications

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

From the specifications we can compute the following requirements on the injection system (Table 2).

Table 2: Injection requirements

Energy, GeV	3
Circulating current, A	0.5
Circumference, m	791.9
Revolution period, μs	2.6
RF frequency, MHz (wavelength, m)	500 (0.6)
Circulating charge, μC	1.3
Total number of buckets	1320
Number of filled buckets	~1040
Charge per bucket, nC	1.25
Current per bucket, mA	0.48
Lifetime, min	180
Interval between top-off cycles, min	1
Current variation between top-off cycles	0.56
Current variation between top-off cycles, mA	2.8
Charge variation between top-off cycles, nC	7.3
Damping time, ms	75*

TOP-OFF NUMEROLOGY

As an example we assume multi-bunch injection with 40 bunches in the macro pulse. We will fill the storage ring buckets sequentially, i.e. first top-off cycle fills buckets 1…40, second one 41…80, third one 81…120, etc. Therefore, after 26 top-off cycles (26 min) the injection comes back to the first 40 bunches. We use the following expression of estimating the bunch pattern non-uniformity†:

$$\Delta I_b / I_b = \left(1-\exp\{-\Delta t_{TO}/\tau\}\right)\cdot N_b / \left(N_m \cdot \Delta t_I \cdot f_{inj}\right) \quad [1]$$

where N_b is the number of bunches in the ring, N_m is the number of bunches in the macro pulse, f_{inj} is the repetition rate, Δt_I is the time interval for a single top-off cycle.

This results in bunch pattern non-uniformity of 15% (peak-to-peak). In this mode of top-off injection the injected macro pulse consists of 40 bunches with 180 pC per bunch at 3 GeV separated by 2 ns (optionally, 4 or 8 ns for non-sequential fill).

Although the above example demonstrates the logic used to determine fill strategies, user requirements on fill patterns are not yet defined and may change over the life

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of the machine and there may be special operating modes for specific users. In practice the bunch trains may vary from single bunch to 150 bunch trains. The ring will have from one to four or more ion gaps to reduce ion trapping. It may be desirable to have a "camshaft" bunch in the ring. For this we must consider the option for the NSLS-II injector to work in the single-bunch mode with as high a charge per bunch as possible to inject into the high-intensity (and hence low lifetime) bunch without interfering with the routine top-off operation..

Some facilities [5,6] have had to implement bunch by bunch monitoring diagnostics and fill algorithms to fill low current bunches. At SLS the "hunt and peck" ("H&P") mode of injection is required to maintain bunch pattern uniformity or else suffer from beam motion induced by BPM aliasing the fill pattern modulation into the orbit feedback.

A standard mode of injection when bunch pattern is being searched for a bucket with a minimum charge over the whole pattern and this same bucket is being injected into during the next top-off cycle. This single bunch injection approach cannot meet the demands of the NSLS-II injection rate of 7-8 nC per minute at one injection per minute since an individual bunch has only 1.25nC.

Currently we are working on assessing possible causes of the bunch pattern non-uniformity during top-off. It has been shown that 10% bunch-to-bunch variation in the injected macro pulse does not cause bunch pattern to deteriorate out of the design limit given by Table 1. We are also exploring various options of the "H&P" mode for a macro pulse injection. One of the options is the direct "H&P", when the charge per bunch in the macro pulse is being uniformly scaled corresponding to the average loss of the charge in the portion of the pattern to be filled. This allows removing all long-wavelength variations of the charge per bunch in the pattern that are longer than the macro pulse length.

Another option is in pre-modulation of the macro pulse exiting the gun with a pattern that corresponds to the inverse replica of the missing charge in the storage ring buckets to fill. The actual hardware design is under discussion.

Lastly there is a way of stacking bunches with a different amount of charge in the booster for accumulation of a desired bunch pattern in the injected macro pulse. In this case the booster stays at the injection energy (which is required to be sufficiently high to ensure damping) during the accumulation process and the gun produces each time a single bunch with the desired amount of charge. After accumulation of all bunches the whole macro pulse is being accelerated and injected into the corresponding ring buckets is highly desirable.

For duration of the initial fill we use the following expression[2]:

$$\Delta t_{fill} = \frac{N_b \cdot \left(I_{inj} / I_b \right)}{f_{inj} \cdot N_m} \qquad [2]$$

where I_{inj}/I_b is the ratio of current in the injected bunch to the nominal current in the storage ring bucket. Assuming the parameters from Table 2 we can get the duration of initial fill of about 3 minutes.

BOOSTER PARAMETERS

The linac injects into a full energy booster which in turn injects once per minute into the storage ring in top-off mode. The booster design parameters are listed in Table 3.

Table 3: NSLS-II booster lattice parameters at 3 GeV

Parameter	NSLS-II
Energy range [GeV]	0.2-3 (3.6)
Circumference [m]	158.4
Emittance [nm]	26.6
Repetition rate [Hz]	1
RF frequency [MHz]	499.654
RF voltage [MV]	1.2
RF acceptance [%]	0.91
Beam current [mA]	28
Momentum Compaction	0.0072
Rad. loss per turn [keV]	625

The 158.4 meter circumference results in a 528 ns revolution period. Assuming a 100 ns kicker rise and fall time this limits the linac pulse train for injection to the booster to ~300ns.

LINAC REQUIREMENTS

Requirements on the linac beam quality are being defined to yield low-loss injection into booster. Values of the injected beam emittance and energy spread affect choice of the stay-clear aperture in the booster ring. In turn, the sizes of stay-clear apertures affect cost of magnetic elements and power supplies, as well as, booster power consumption. On other hand, insufficiently small stay-clear aperture leads to beam losses at injection.

Keeping these considerations in mind we developed preliminary requirements on the linac beam (Table 1).

Table 4: Preliminary requirements on the linac beam parameters

Parameter	Value
Energy	170-270 MeV
Emittance, X/Y, $4\beta\gamma\sigma_x\sigma_{x'}$	100 mm·mrad
Energy spread, single bunch	±0.5%
Energy spread, multi-bunch	±1%
Bunch train length	40-150 bunches, 2 ns
Bunch charge, single bunch	from 10 pC to 2.5 nC
Bunch charge, multi-bunch	<15 nC total

We have chosen linac energy of 200 MeV, which is higher than in most of the modern light sources. High linac energy is advantageous from several aspects. Firstly, more linac tanks increases reliability of the system by increasing redundancy. Secondly, higher injection energy results in higher fields in the booster dipoles, easing their design and field correction. Lastly, higher linac energy reduces relative energy spread and, therefore, horizontal size of the booster beam at injection.

Low linac emittance allows to reduce vertical beam stay-clear. A critical, and difficult to meet requirement is the energy spread of +/-0.5% for the short bunch trains carrying high charge. In this case the energy spread is dominated by the beam loading that requires accurate compensation. One of the compensation methods is in so-called A-modulation as implemented in THALES [THALES]. In this compensation scheme the energy droop due to the beam-loading in the first tank is canceled in the timing the fill of the second tank so that the gradient is increasing. Additional linac tanks are helpful in optimizing this compensation, as well as providing redundancy in the event of a klystron failure.

Summing up all of the requirements we may conclude that the range of the NSLS-II linac parameters spreads outside of what has been accomplished in the recent turnkey procurements (see for example [ACCEL], [THALES]). Development of the techniques and hardware to accomplish the NSLS-II objective will be the subject of ongoing R&D activity for NSLS-II.

The injector linac consists of the following sub-systems:

- Planar triode electron gun and high voltage deck
- 500MHz sub-harmonic prebuncher
- 2.998 GHz prebuncher
- 2.998 GHz final-buncher
- 2.998 GHz accelerator tanks
- Focusing magnets (quadrupoles, solenoids)
- Instrumentation and diagnostics
- Klystron and modulators
- Low level rf controls

The layout of the linac will depend on the accelerating structure length and gradient. A minimum of three tanks and three klystrons is predicated by the requirement of being able to continue injection, albeit at a lower energy, with the loss of a single klystron. A waveguide switch network will be used to switch the second klystron to feed the first accelerating structure and bunchers in the event the first klystron fails.

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