NSLS-II RADIO FREQUENCY SYSTEMS *

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Abstract

The National Synchrotron Light Source II is a 3 GeV X-ray user facility commissioned in 2014. The NSLS-II RF system consists of the master oscillator, digital low level RF controllers, linac, booster and storage ring RF sub-systems, as well as a supporting cryogenic system. Here we will report on RF commissioning and early operation experience of the system.

INTRODUCTION

The NSLS-II radio frequency system was designed as a whole from the master oscillator, its distribution to subsystems, from digital field controllers to high power amplifiers driving normal and superconducting cavities. The RF drives the grid of the planar triode in the DC electron gun creating the electrons that are bunched and accelerate to 200 MeV in the 2.998 GHz linac, are captured and accelerated in the 499.68 MHz bucket of the booster RF and accelerated to 3 GeV. The 3 GeV electrons extracted from the booster are injected into the RF buckets of the superconducting cavities in the storage ring where they are accumulated up to 500 mA. This paper describes these systems.

MASTER OSCILLATOR

The master oscillator is the reference frequency for the RF systems as well as the master clock for the timing system. Because it is the ultimate source of amplitude and phase noise imposed on the beam through the RF cavity field, specifications from x-ray beam line requirements were derived [1]. These are given in Table 1.

Table 1: Longitudinal Beam Stability Requirements

	Phase Jitter $\Delta\theta$ [°]	Momentum Jitter $\Delta p/p$ [%]
Timing-dependent experiments	0.14	0.005
Vertical divergence (from momentum jitter)	2.4	0.09
10% increase in σ_δ due to filamentation	1.8	0.065
Vertical centroid jitter	0.82	0.03

In order to meet the demands of timing experiments we took the timing dependent experiments requirements of 0.14 degrees phase jitter and 0.005 % momentum jitter as the requirement for the RF system. The master oscillator must contribute no more than a fraction of this. We chose an Agilent E8257D synthesized signal generator with low phase noise options. Frequency agility is required for a number of applications, including measurement of chromaticity, measurement of dispersion and compensation of orbit length due to wavelength shifters. Of these, chromaticity measurements are the most demanding. With the parameters of the NSLS II baseline design ($\alpha = 3.68\ 10^{-4}$, $\gamma = 5871$, $f_{rf} = 500$ MHz) and the assumption that the tune change $\Delta\nu_{x,y}$ should be at least 3 times the tune spread $\sigma\ \nu_{x,y}$ to get good resolution for the tune measurement when measuring small chromaticity's down to $\xi_{x,y} = 0.1$, and an educated guess for the tune spread of $5.\ 10^{-3}$ in both transverse planes, we obtain $\Delta f_{rf} = -\ \alpha\ 3\sigma\ \nu_{x,y}\ f_{rf} / 0.1 \approx \pm 29$ kHz

The generator allows for software commanded phase continuous frequency modulation which will be used for the above measurements as well as in a slow frequency or "radial" loop to make corrections for small changes in electron beam orbit caused by seasonal or diurnal temperature variations in ring circumference. The MO output is amplified and split to be distributed to the storage ring RF cavity field controllers, injector RF systems, the timing system, a streak camera and the bunch by bunch feedback system.

DIGITAL CAVITY FIELD CONTROLLER

The starting point for the NSLS-II cavity field controller was the architecture of the SNS controller designed by Doolittle et al [2]. This architecture utilizes up/down conversion from RF to the 50 MHz IF frequency using LO and AD/DA clocks derived from the Master Oscillator frequency, which is also the synchrotron ring RF frequency. New hardware was designed [3] for the NSLS-II RF frequency of 499.68 MHz. The most significant improvement was in the development of new firmware to provide new capability necessary for the operation of a synchrotron. Given the number, types and variety of cavities that they are to control, modular FPGA code and conditional compilation was used. For example, instantiation of feedback, interlock components and ramp generators are conditional depending on the needs of the RF system towards which the build is targeted.

Storage Ring Compilation

The Storage Ring compilation contains the feedback logic with set-point generation and feedback gain control. It also contains a ramp down block which when triggered by an external interlock ramps the fixed field set point to zero in a 1ms timescale. This prevents tripping the transmitter on reverse power as would happen should the RF drop out in microseconds.

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Booster Ring Compilation

Provides a ramped set point output from a feedback ramp table in logic that linearly interpolates between 512 I/Q pairs of waypoints. This table is loaded by block transfers from the host interface and is triggered at the 1 Hz booster repetition rate.

Linac Compilation

Provides ramped set points from a feedforward table in logic that outputs 1024 discrete points. This table like the feedback ramp table mentioned above is loaded by block transfers from the host interface.

Injector Master Oscillator Phase Correction

The Master Oscillator (MO) signal must be routed from the Storage Ring RF building to the injector building, some 200 meters. Given the specification of low phase drift RF cables and the tolerance on building temperature up to 5-6 degrees of phase shift was expected. To correct for this two low loss, phase stabilized 7/8 inch coaxial cable were routed between the buildings. The MO is sent via a dedicated cavity field controller (CFC), to the injector through one cable, the signal split and returned through the second. The CFC then measures the phase difference and corrects for half the error since we assume the phase drifts of the two cables are equal and we are trying to correct for the one-way trip to the injector. This also gives us a convenient point to adjust the phase of the injector with respect to the storage ring to tune injection efficiently.

Network Analyser Controller Compilation

Provides ramped frequency output and up to 8 input channels acting as a multi-channel network analyser. The network analyser function will be used to take RF amplifier-cavity and RF-beam transfer functions used in calculating RF feedback loop parameters, and eventually to include the beam phase in the RF feedback loop.

LINAC

The linac was specified to operate at the 6th harmonic of the booster and storage ring nominal frequency of 499.68 MHz to allow bunch to bucket injection into the booster. Every sixth bunch in the 2998.08 MHz linac RF is filled by driving the grid of the planar triode electron gun at 499.68 MHz and using a 500 MHz sub-harmonic pre-buncher and 3 GHz pre-buncher to shorten to electron bunch to <330 ps to fit within a single linac bucket. The electrons are then accelerated through a 12-cell traveling wave (TW) final buncher and four 5-meter TW accelerating structures to the final energy of 200 MeV. The pre-bunchers are driven by solid state amplifiers while the TW final buncher and four accelerating structures are powered by two 42 MW peak klystron tube amplifiers. The klystron modulators use 42 solid state IGBT switches operating at 1.2 kV each driving an individual primary turn on the pulse transformer. These multiple primaries are coupled through the flux in the core to a single secondary winding. A third klystron can be switched via waveguide combiners to either klystron 1 or klystron 3 position providing redundancy. This design has resulted in a very high availability the past two years.

BOOSTER RF SYSTEM

A 500MHz 90kW IOT is used to power the PETRA-like cavity for the booster. The cavity produces a ramped accelerating voltage from 200 kV to 1200 kV required to accelerate the beam from 200MeV to 3GeV. The IOT is well matched to the peak power requirement of ~65 kW and average power of 20 kW. The tube is assembled on a cart which includes a focusing coil and input/output circuits. This modular approach allows switching out a tube assembly in about two hours. The transmitter is controlled via a Programmable Logic Controller (PLC) which communicates with the NSLS-II EPICS Control System to ensure proper operation and shutdown in the event of an interlock fault.

STORAGE RING RF

The storage ring lattice is designed with 2 RF straight sections each having two 499.68 MHz superconducting (SRF) single cell cavities and a one 1499.08 MHz two cell harmonic cavity. Currently only one 499.68 MHz cavity is installed although the second 499.68 cavity has been built and tested as well as a 1499.04 MHz SRF harmonic cavity. These latter cavities will be installed in subsequent shutdowns scheduled over the next year. The second RF straight is to be built out as additional RF power is required with the addition of new insertion devices over the next several years. The dedicated 814 W at 4.5 K liquid helium plant for the storage ring SRF is sized to cool all six cavities in both RF straights. It has been installed and commissioned and has been in operation for the past year.

Klystron Transmitters

Klystron tube based transmitters were chosen for the first two storage ring transmitters based on cost, maturity of design and compressed installation and commissioning schedule (less than two years from contract). These have proven to be robust and dependable for the first two years of operation, including the past year of beam operations. The 300 kW CW klystrons are powered by a solid state pulse switch modulated high voltage power supply (HVPS). The HVPS utilizes a twelve pole step up transformer (480 V to 50 kV) in a delta-wye configuration with individual secondary's that feed 86 solid state switches wired in series to provide the 50 kV, 12 A for the klystron cathode voltage. A modulating anode supply can adjust the tube bias for better efficiencies at lower output powers. There was concern about the sub-harmonics of the switching power supply (f_{switch} /86 modules) aligning with the synchrotron frequency and driving the beam. The synchrotron frequency is between 2-4 kHz depending on RF voltage, and with a switching frequency of 110 kHz the switching sub-harmonics are n times 1.28 kHz, so the 2.56 kHz sub-harmonic could drive the beam. Therefore the HVPS switching frequency was re-programmed to 137.5 kHz to steer clear of the synchrotron tune.

499.68 MHz Superconducting RF Cavities

The CESR-B type single cell SRF cavity was chosen for the storage ring fundamental RF. The design of the NSLS-II cavities differ from those previously produced in two respects: First, they had to meet new DOE rules on equivalence with the ASME pressure vessel code. This led to several design changes in order to comply with ASME: thicker niobium sheet throughout (3.4mm vs. 3.2mm in most areas, 4mm in the waveguide), thicker bellows on the helium vessel, and an increase in the diameter of the burst disk pressure relief vent pipe from 2 inches to 3 inches. In addition, in order to meet the full-build out requirements of a total of 4 times 270 kW RF power delivered to the beam and a total RF voltage of 4.9 MV (1.225 MV/cavity) the coupling had to be increased to achieve a Q external of ~65,000 +/- 20%. The measured Q external as fabricated is 79,000.

1499.04 MHz Passive Harmonic SRF Cavities

The design goal of the 1500 MHz harmonic cavity was to achieve an R/Q of the π-mode of < 90 ohms [4], an R/Q of the 0-mode of < 1 ohm and a large beam pipe diameter to reduce the wake field heating of the ferrite mode dampers to acceptable levels. These goals were achieved with a beam pipe diameter of 120 mm, an iris diameter between the two cells of 38 mm and iterating the cell lengths to reduce the 0-mode impedance. The cavity geometry is shown in Figure 1, and the achieved geometrical impedances in Table 2.

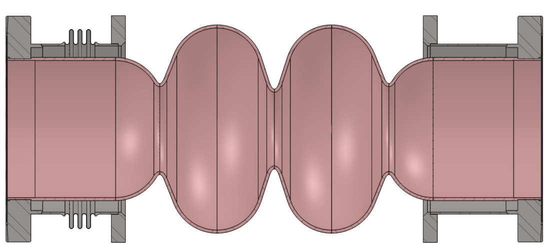

Figure 1: 1500 MHz cavity geometry.

Table 2: NSLS-II Harmonic Cavity Parameters

Freq(π-mode)	MHz	1499.25
R/Q (Pi)	Ω	88
Accelerating Voltage	MV	1.0
Freq (0-mode)	MHz	1478.03
R/Q (zero)	Ω	0.15

COMMISSIONING AND EARLY OPERATIONS

The installation of the superconducting cavity was completed without any time for testing without beam and the system commissioned with beam to 1.2 MV cavity field voltage during the first run, limited by cavity outgassing. During the second run 2 dedicated RF conditioning shifts were given to the RF group and the cavities conditioned up to 1.8 MV, the zero current limit based on the reverse power specification of the RF window. Beam current was steadily increased to 200 mA without any system adjustments other than RF feedback gain. The first fill to 200 mA is shown in Figure 2.

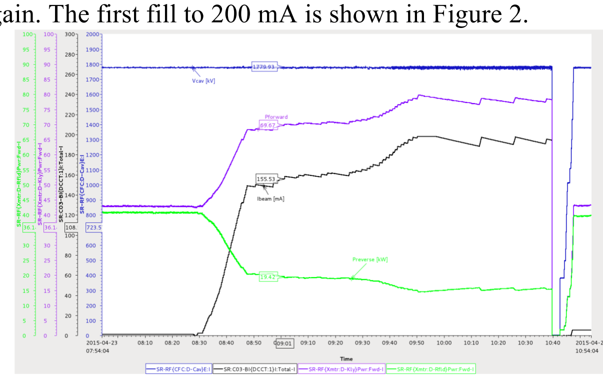

Figure 2: Cavity field, forward and reverse power and beam current plot from 0 to 200 mA injection. Beam was dropped intentionally as feedback gain limits were explored.

CONCLUSION

A robust RF system design has been successfully built and commissioned at the NSLS-II and is in early operations. 200 mA of stored current has been achieved with the only adjustment being the tweaking of RF feedback gains.

ACKNOWLEDGMENT

The NSLS-II RF systems bear strong resemblance to those in other 3rd generation light sources for good reason: the generosity of Mark de Jong of Canadian Light Source, Chaoen Wang of Taiwan LS and to Morten Jenson of Diamond LS who shared with us their successes and warned us of pitfalls to avoid.

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