RADIO FREQUENCY SYSTEM OF NSLS-II INJECTOR LINAC FOR MULTI-BUNCH-MODE BEAMS*

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Abstract

The Multi-Bunch Mode (MBM) beam injection operation of NSLS-II LINAC requires a beam-loading compensation for its RF field. That requirement has a significant impact on its radio frequency system (RF), in both the low-level RF control and the high-power klystron transmitters. Specifically, for the RF control, it requires the output vector modulation have enough bandwidth to be able to respond the transients by the MBM beams of 40 to 300 ns long. For the high-power RF transmitters, it requires the klystrons operate in a near-linear region to be able to respond the linear RF control for the beam-loading compensation, which means a need of ~30% extra RF power overhead, compared to the single-bunch mode operations. The digital signal processing and the network configuration for the RF controllers are also the important areas in the implementation. The original system design was driven by the MBM beam operation requirements, and our system upgrade today continues to be guided by the same principles.

SYSTEM OVERVIEW AND DESIGN CONSIDERATIONS

LINAC Design Parameters

The NSLS-II LINAC is a 2.998 MHz, 200 MeV Pre-Injector to the following 3 GeV Booster Synchrotron which in turn serves as the injector to the final Storage Ring. It delivers minimum 0.5 nC of charge in Single-Bunch Mode, and up to 15 nC in Multi-Bunch Mode (MBM). The length of an MBM varies from 20 to 150 beam bunches, or 40 to 300 ns in time. The basic parameters are listed in Table 1 below, and more details can be found in Refs. [1, 2].

Table 1: NSLS-II LINAC Basic Parameters

Nominal Energy	200 MeV
Minimum Energy	170 MeV
Repetition rate	Single-shot to 10 Hz
Long Pulse Mode	
Pulse train length	40 – 300 ns
Bunch numbers at 500 MHz rep. rate	20 – 150
Maximum charge per pulse train	15 ns
Relative charge variation between bunches	< 10%

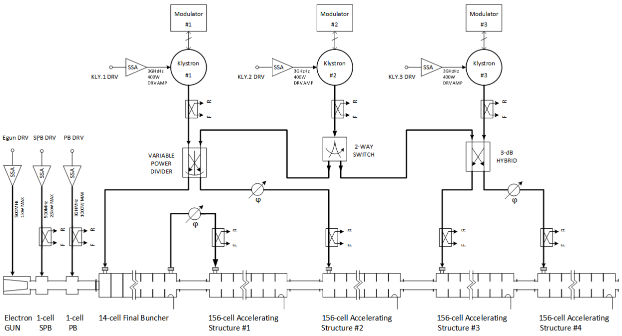

Figure 1: NSLS-II LINAC High-Power RF Configuration.

High-Power Klystron Transmitter System Design for High Operation Availability

The LINAC RF chain starts with the RF modulating grid PA for a YU-171 Electron Gun, followed by a 500 MHz Sub-Harmonic Buncher, a 3 GHz Pre-Buncher and a Final Buncher as the LINAC front-end. The following four traveling-wave structures LINAC powered by two 45 MW klystrons bring the beam energy to the required 200 MeV [1]. The configuration of the LINAC high-power RF system is shown in Figure 1. There are three 3 GHz, 45 MW klystrons in this system, two of which are needed for running the 200 MeV routine operation. The klystron station #2 in the middle functions as a standby hot spare, which can be readily switched in the system to substitute Klystron #1 or #3 should either one fail.

The 45 MW klystrons (Canon E37302A) are powered by three COTS high-performance, solid-state switching modulators (SSM) by ScandiNova [3]. These SSM's produce the klystron beam HV pulses that have a very smooth flattop, which helps the LINAC beam energy jitter and dispersion stay within the specifications.

Digital RF Transmitter Front-end

The architecture of the digital RF controller as shown in Figure 2 is similar to that of standard base-station SDR (Software-defined-Radio), comprised of a digital receiver front-end Rx for the measurement and monitoring the RF field vectors in the cavities, and a digitally-controlled RF vector modulator front-end Tx at the transmitter input

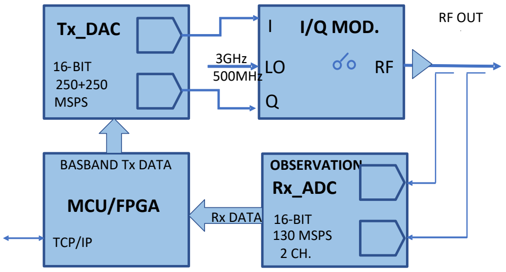

Figure 2: LINAC RF control front-end architecture.

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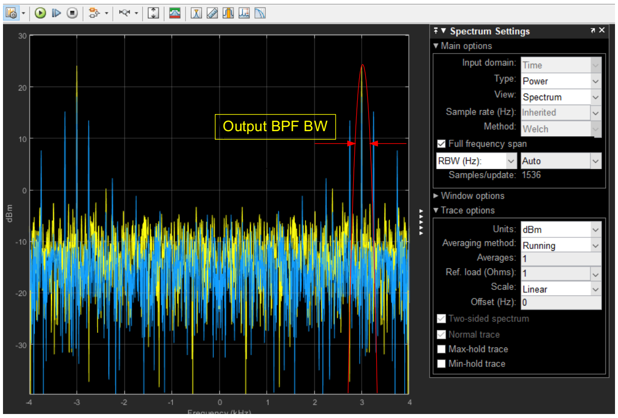
performing the required pre-distortion (PD) RF modulation for beam-loading compensation (BL) [3].

For compensating the BL of the MBM beam bunch trains as short as 40 ns, the bandwidth of the PD modulation is a crucial performance to achieve in the design. It is estimated that a minimum 100 MHz 3 dB bandwidth is necessary for the PD modulation to be effective for this application.

In order to achieve that level of the control bandwidth, two DAC's running at 250 MHz clock rate are used for the I/Q baseband data update, which results in a modulator output spectrum that has a far-spaced sideband spectral lines from the carrier as shown Figure 3. This spectral structure allows the use of wideband spectrum-cleanup filters at the output, thus maximizes the final control bandwidth.



Spectrum Settings

Main options

Input domain: Time
Type: Power
View: Spectrum
Sample rate (Hz): Inherited
Method: Welch
☑ Full frequency span
RBW (Hz): Auto
Samples/update: 1536

Window options

Trace options

Units: dBm
Averaging method: Running
Averages: 1
Ref. load (Ohms): 1
Scale: Linear
Offset (Hz): 0
☑ Two-sided spectrum
☑ Normal trace
☐ Max-hold trace
☐ Min-hold trace

Figure 3: Far-spaced sidebands around the carrier in Tx front-end output spectrum.

Digital RF Receiver Front-end

The digital RF receiver front-end (Rx) for the LINAC RF field measurement and monitoring is a standard SDR receiver, utilizing a quadrature-sampling for the vector demodulation of the RF signals.

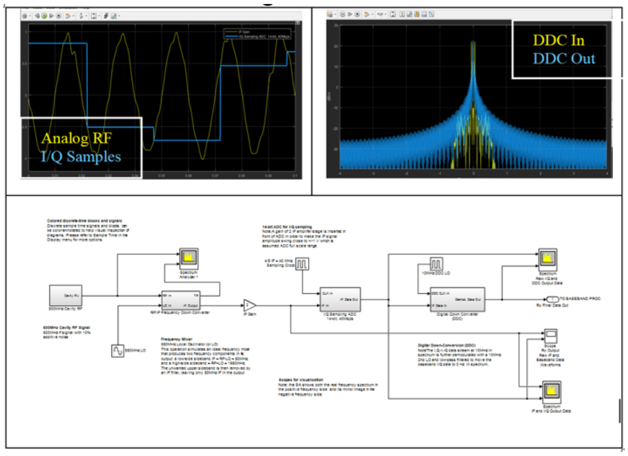


Figure 4: Rx ADC I/Q sampling (up-left); Spectra of Rx I/Q data at DDC In/Out (up-right); simulation model of Rx front-end (bottom).

The digital RF vector detection is a 2-step process. The analogue RF signal is first frequency-down-converted to an IF, and the IF is then gone through the 1st digital demodulation by a quadrature sampling, or I/Q sampling, at a special rate of Fs = 4/3*IF. The spectrum of this raw I/Q data is at an offset frequency of 1/4Fs. The offset I/Q data spectrum is than shifted to the baseband in the subsequent 2nd digital demodulation by a digital down-converter (DDC). A simulation model of the Rx front-end and the signal transformations are illustrated in Figure 4.

RF Control System Integration

One of the most important operational aspects for the RF control is its integration with the Accelerator Controls Infrastructure, which primarily involves connectivity of the controls network and the timing network. In NSLS-II LINAC, all six RF controllers are placed in a private subnet and connected to an EPICS IO/C server in the same subnet first. The LINAC RF Control as whole is then merged with the global controls through this server. A local Timing-Event Receiver (EVR) provides all the timing triggers to the RF controllers and the klystron modulators. Figure 5 below shows the topology of the LINAC RF controls subnet.

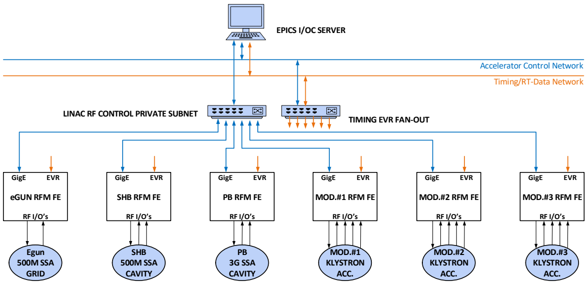


Figure 5: LINAC RF control subnet configuration.

BEAM-LOADING AND CORRECTION

NSLS-II LINAC uses the constant-gradient accelerating structures. A simulation performed during the system final design shows that for a total charge of

$$q_{\text{tot}} = 17\ \text{nC} + 20\% = 20.4\ \text{nC}$$

distributed in the bunch trains with the length of 30, 80, and 160 bunches, the resultant beam-loading causes the RF field to droop from 3.4% for the 300 ns bunch train to 5.3% for the 60 ns bunch train as shown in Figure 6.

This amount of RF error has far exceeded the tolerance, and therefore it must be corrected with the means such as

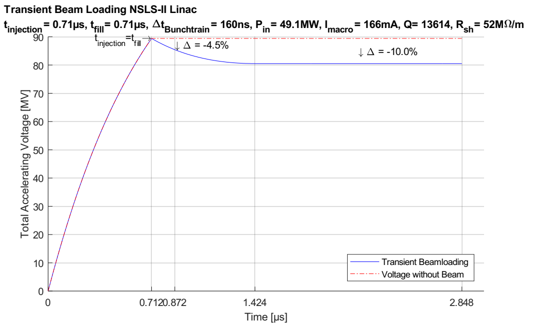


Figure 6: Beam-loading simulation for 180 ns MBM beam case.

a Feed-forward Control (FF) in the digital transmitter front-end.

The method of using the FF control for compensating the MBM beam-loading is straightforward. Similar to the Pre-Distortion modulation (PD) used in the telecom transmitters, the FF control adds pre-determined patterns to the baseband modulation waveform data for both the phase and amplitude to counteract the effects of the BL. Take the 500 MHz Sub-Harmonic Buncher cavity (SHB) in NSLS-II LINAC for example. The beam phase in the SHB is almost 90 degrees off with the RF phase, and time constant of the cavity causes the magnitude of the BL effect to grow gradually over the time of the beam bunch train, and the RF vector to rotate in the phase and drift in the amplitude, as shown in the MATLAB simulation plot in Figure 7 in the left. To cancel out this distortion in the RF field, the FF control adds a pre-distortion pattern to the SHB RF vector modulation waveform data. When the FF PD pattern matches the pattern of the BL, the distortion in the RF field is removed as shown in the plot in the right.

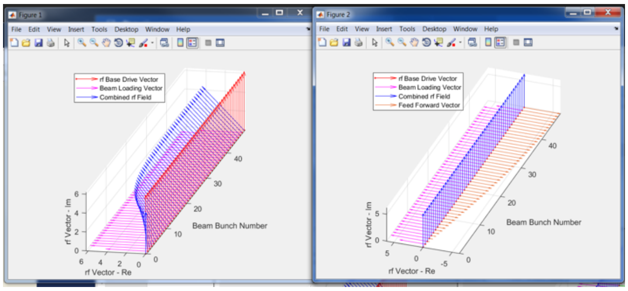


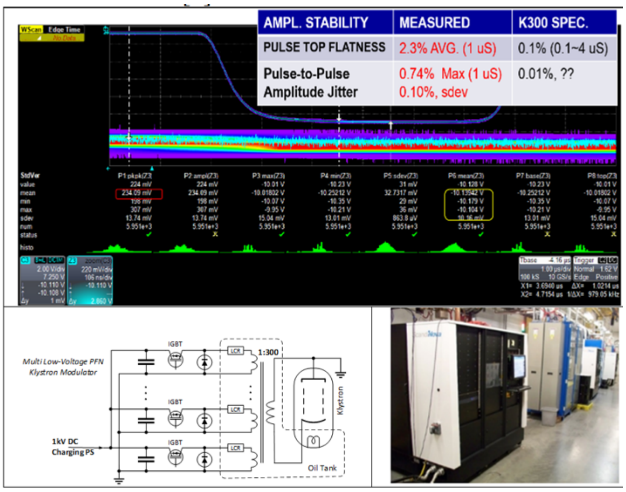
Figure 7: Simulation of feed-forward control for SHB beam-loading.

HIGH-PERFORMANCE SOLID-STATE KLYSTRON MODULATOR

The NSLS-II LINAC beam physics specifications in the energy jitter and dispersion drive the need for a stable klystron RF output power. To help to meet that requirement, a high-performance, solid-state switching klystron modulator (SSM) was chosen over the conventional PFN type. This SSM is a Commercial off the Shelf (COTS) solution by ScandiNova, it has the capability of producing the pulsed HV for the klystron with a high degree of stability and the pulse waveform with a very smooth flattop, as shown in a performance test result in Figure 8. The compact size of SSM occupying less the floor space in the LINAC gallery is also a plus. More detailed description about the SSM can be found in Ref. [4].

STATUS AND UPGRADES

The LINAC RF system has been successfully operating since its commissioning in 2013. To improve the operation reliability of the klystrons, in 2016, we started the upgrade of all the Thales klystrons to the more reliable and more powerful Toshiba/Canon E37302A klystrons. For running the new klystrons, the original K2 model SSM's also needed to be upgraded to the new K300 model. Up to the date, we have completed the high-power RF upgrade. The upgrade for the RF control is currently underway [4].



AMPL. STABILITY	MEASURED	K300 SPEC.
PULSE TOP FLATNESS	2.3% AVG. (1 uS)	0.1% (0.1~4 uS)
Pulse-to-Pulse Amplitude Jitter	0.74% Max (1 uS) 0.10%, sdev	0.01%, ??

Figure 8: Performance of K300 solid-state switching klystron modulators used in NSLS-II LINAC.

CONCLUSIONS

The experience of NSLS-II LINAC proves that a successful RF system design is the one that is driven by the beam physics specifications, and that principle was carried through out of the entire planning and implementation process. Making use of COTS solutions is also an important part of our success.

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