ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-TUPLH19

UPGRADE AND OPERATION EXPERIENCE OF SOLID-STATE SWITCHING KLYSTRON MODULATOR IN NSLS-II LINAC*

H. Ma†, J. Rose, Brookhaven National Laboratory, Upton, NY, USA

Abstract

The NSLS-II synchrotron light-source at BNL uses three S-band, 45MW klystrons in its injection LINAC. At the core of each klystron station design is a novel solid-state switching modulator (or SSM). Compared to the conventional PFN klystron modulators, the main advantages of the SSM include the compact size requiring a smaller footprint in the LINAC gallery, and a very flat top in the produced klystron HV pulse waveforms. The flatness of the HV pulses is very important to NSLS-II LINAC that runs multi-bunch beams for keeping the beam energy dispersion within the tolerance. The principle of the SSM is fairly simple. It uses a large number of relatively low-voltage switched charging capacitor cells (or SU's) in parallel. A specially designed, high step-up ratio, pulse transformer in the oil-tank with the same number of primary windings (as that of SU's) combines the power from all the SU's, and steps up to the required ~300kV klystron beam voltage. The operation experience at NSLS-II has proven the performance and reliability of the SSM's. The BNL Model K2 SSM's are currently being upgraded to Model K300 to run more powerful, and more cost-effective Canon's E37302A klystrons.

KLYSTRON RF POWER PLANTS

To achieve the designed 200 MeV beam energy, the required rf power level would be in 70~100 MW range. For the S-Band rf power of this level, Klystron is still the only feasible choice, despite of the progress in cost/Watt ratio being made for the solid-state rf amplifiers in recent years.

As previously mentioned, NSLS-II Injector LINAC was designed to have the capability of filling up to 150 Booster rf buckets in one shot with the long multi-bunch beam patterns. That requires that the LINAC pulsed rf maintain a constant flat top in its amplitude/phase waveform envelope for about 1 us period (for 150 bunches/300nS beam) to allow the long bunch trains to pass through the LINAC with the energy dispersion within the designed tolerance. For this reason, the rf pulse compression device SLED cannot be considered for gaining extra rf peak power as the severely distorted and lopsided waveform that a SLED outputs is inherently incompatible with the multi-bunch beam operation. The long bunch train length in MBM operation also poses an additional issue of beam-loading on the rf fields. NSLS-II LINAC design adopted a digital rf modulator in the rf transmitter front-end (or RFM) to generate a Pre-distortion waveform for the beam-loading compensation. The details about the digital RFM is reported in a companion paper [1]. The photos in Fig. 1 show the high-power LINAC rf equipment, while the block diagram in Fig. 2 shows the function blocks of the system.

Figure 1: NSLS-II Injector LINAC tunnel (left) and Klystron Gallery (right).

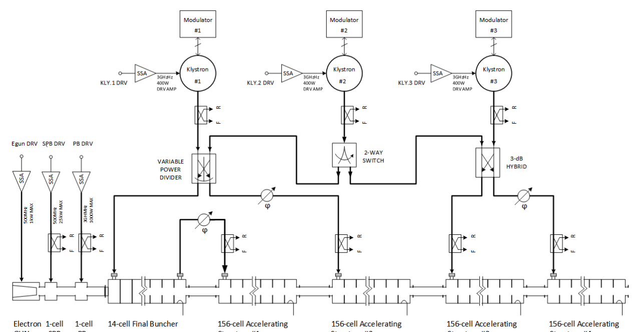

Figure 1: The NSLS-II LINAC rf power plants is comprised of three Solid-State RF PA's and three 45MW klystrons for the following 4-section 3GHz accelerating structures. The klystron in position #1 and 3 are for normal operation, while the one in #2 is a backup station.

The NSLS-II Injection LINAC was manufactured by Research Instruments, GmbH per NSLS-II-BNL's specifications, with its design consideration emphasized on achieving the highest operation reliability while using the new technology where it is feasible [2, 3].

SOLID-STATE SWITCHING KLYSTRON MODULATORS

The choices for the NSLS-II LINAC modulators were also carefully examined. The traditional approach for the short-pulsed klystron modulators is to use a single lump-sum Pulse Forming Network (or PFN) with hard-tube (Thyratron) switches to produce HV pulses between 2 and 4 microseconds long. The diagram in Fig. 3 depicts a typical design of the traditional PFN modulator.

* This manuscript has been authored by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
† hengjie@bnl.gov

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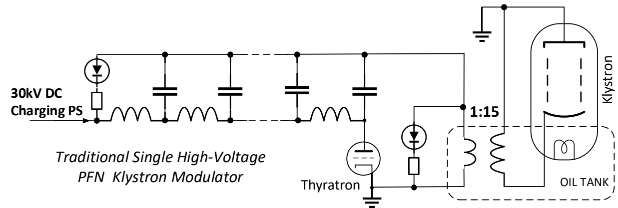

Figure 2: The traditional PFN klystron modulator with a single PFN section.

The PFN design uses a single lump-sum pulse-forming network with a few larger charging capacitors and inductors. The lump-sum PFN operates at a fairly high voltage, typically over 30kV. The step-up pulse transformer in the klystron oil tank raises the 30kV pulse from the PFN to the required ~300kV for the klystron. Our own experience and study of others' experience lead to a conclusion that the failures of the PFN/hard tube modulators dominate the LINAC downtime, with rates three times those of the klystron tube and its filament/core bias power supplies [4]. In summary, the major short-comings associated with the traditional single PFN modulator design include

- The very-high voltage operation puts the components under a constant extreme stress, resulting in frequent failures,
- The very-high voltage operation also requires larger spacing between the components due to corona discharging issue, and thus the PFN modulators are typically bulky, and
- The ripples on the HV output waveforms due to limited number of resonating sections in the PFN. The HV ripple issue with the PFN modulators is particularly problematic for the multi-bunch mode operation of NSLS-II LINAC.

To overcome the fore-mentioned issues with the traditional PFN modulators, in the past decade some new compact solid-state switching klystron modulator designs had been developed for both scientific and medical LINAC applications. Among the competing designs, the one by Crewson Engineering/ScandiNova [5] has been successfully commercialized and was chosen for NSLS-II LINAC application.

The simplified diagram in Fig. 4 illustrate some of key factors that make Crewson/ScandiNova design successful;

- Each low-voltage PFN cell (or SU) operates at pulsed ~1kV/1500A, and it is comprised a relative small charging capacitor, an IGBT switch, and a protective free-wheeling diode. The components of this voltage/current rating range are easier to source.
- A large number (say 48) of such SU cells are paralleled to produce the required total pulse power for Toshiba E37302A klystron. Because all the SU cells are connected in parallel, the operating voltage of the entire system outside of the klystron oil-tank is still the lower ~1kV, which allows the 48 PFN cells to be packed compactly in eight modules (of six cells each), resulting a much reduced modulator size (typically 1/3 of that of a traditional PFN modulator).
- The special 1:300 step-up pulse transformer in the oil-tank plays a key role in bringing this SU array scheme together. It serves a dual-purpose of combining the pulse power from the SU cells, and stepping up the output voltage to the required klystron beam voltage of ~300kV.

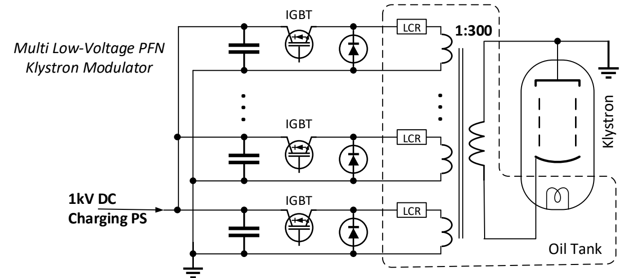

Figure 4: The configuration of NSLS-II solid-state switching klystron modulator with an array of small "PFN" modules which uses IGBT switches and operate in parallel at a much lower voltage (~1kV).

KLYSTRON UPGRADE

The NSLS-II LINAC was designed and commissioned with Thales TH2100 klystrons in 2012. The operation in the following years has experienced an unusually high-rate of Arcing faults and klystron failures. By 2015, less than four years since the commissioning, all four purchased TH2100A klystrons had failed, and we had to run the LINAC with the borrowed klystrons. Due to the high-cost of TH2100A klystron and its relatively short life, continuing to operate our LINAC with this klystron is financially unsustainable. A decision was made in 2015 to replace the Thales klystrons with the comparable Toshiba E37302A klystrons. The key parameters of two klystrons are listed in the table in Fig. 5.

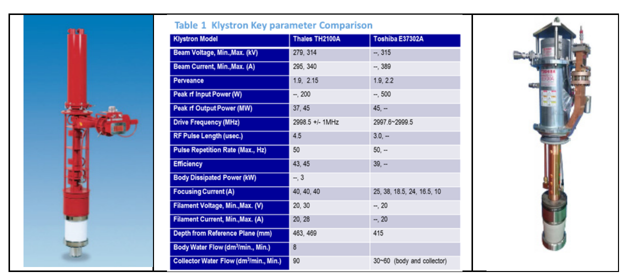

Table 1 Klystron Key parameter Comparison

Klystron Model	Thales TH2100A	Toshiba E37302A
Beam Voltage, Min.,Max. (kV)	279, 314	--, 315
Beam Current, Min.,Max. (A)	295, 340	--, 389
Perveance	1.9, 2.15	1.9, 2.2
Peak rf Input Power (W)	--, 200	--, 500
Peak rf Output Power (MW)	37, 45	45, --
Drive Frequency (MHz)	2998.5 +/- 1MHz	2997.6~2999.5
RF Pulse Length (usec.)	4.5	3.0, --
Pulse Repetition Rate (Max., Hz)	50	50, --
Efficiency	43, 45	39, --
Body Dissipated Power (kW)	--, 3	
Focusing Current (A)	40, 40, 40	25, 38, 18.5, 24, 16.5, 10
Filament Voltage, Min.,Max. (V)	20, 30	--, 20
Filament Current, Min.,Max. (A)	20, 28	--, 20
Depth from Reference Plane (mm)	463, 469	415
Body Water Flow (dm^3/min., Min.)	8	
Collector Water Flow (dm^3/min., Min.)	90	30~60 (body and collector)

Figure 5: The original TH2100A klystron (left) in NSLS-II LINAC was upgraded to the more powerful Toshiba E37302A klystron (right) for an improved performance.

KLYSTRON MODULATOR UPGRADE

A corresponding update for the klystron modulator from the current K2 model to K300 model (both by ScandiNova) also became necessary in order to support the slightly larger Toshiba klystron with an increased beam current from 340A to 389A. Beside purchasing an all new K300 modulator, the existing BNL's ScandiNova K2 modulators are also to be refurbished to upgrade their performance to K300 level with the following necessary modifications highlighted in the block diagram in Fig. 6.

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- Replacing tank top plate and socket for mounting E37302A klystron.
- Add 3 more DC power supplies to power 6 magnets, using 3-PH AC power.
- Add an extra Switch module (from 7 to 8) to handle increased beam current capacity of E37302A,
- Upgrade the K2 modulator controls to the more robust K300 controls.
- Increase the capacity of the cooling water system.

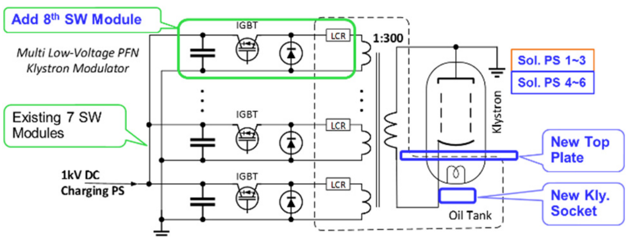

Figure 6: The necessary modification on the old K2 modulator for upgrading its capacity to support the bigger E37302A klystron.

OPERATION EXPERIENCE WITH NEW KLYSTRON AND MODULATOR

The klystron/modulator upgrade process started in late 2016, and so far we have finished the upgrade for the two of the three klystron stations. We first upgrade our rf station #1 with an all new K300 modulator and a brand new E37302A klystron. From more than two year's operation experience with this new klystron/modulator combo, we can definitely conclude that the upgrade is a success. Both the new klystron and modulator have been running very stably and reliably, rarely have arcing fault. Figure 7 shows the performance measurement for the HV pulse-top flatness of 2.3% averaged, and a pulse-to-pulse amplitude jitter of 0.74% Max.

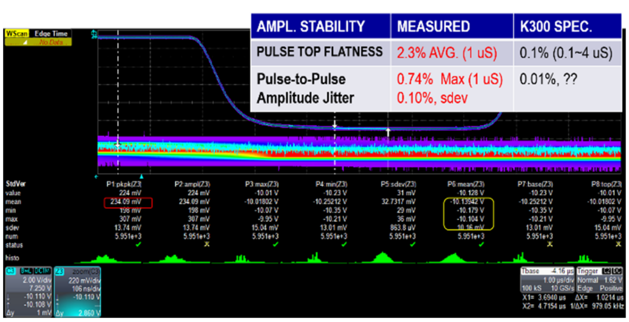

Figure 7: Measured stability performance of BNL's first K300 modulator running with a E37302A klystron.

As a backup plan, we also explored the option of rebuilding the failed TH2100A klystrons. We repaired one TH2100A by CPI, and ran it with one our existing K2 modulator in operation for more than two years. The result was also very good. The rebuilt TH2100A klystron with a CPI cathode has been running very stably, and shows little performance degrade after continuously running for more than two years. Figure 8 shows the stability performance of the CPI-rebuilt TH2100A klystron and K2 modulator combination, with a pulse-top flatness of 2.2% avg., and pulse-to-pulse jitter of 0.38% Max. Repairing the Thales klystrons has proven to be a viable option for us, although in the end we decided to go with the approach of klystron upgrade to Toshiba E37302A for the benefit of its availability and improved performance.

CONCLUSIONS

The klystron and modulator upgrade of NSLS-II LINAC is a success. The new E37302A klystrons and K300 modulators have eliminated the issues we had in the past, and have been running very reliably, and effectively supporting the light source operation since 2017. We plan to finish the upgrade of the remaining two K2 modulators in the near future.

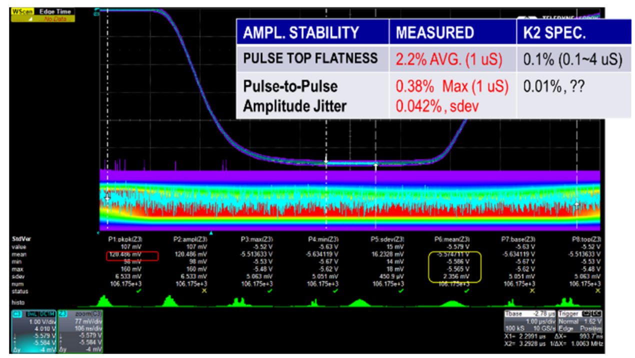

Figure 8: Amplitude stability performance of CPI-rebuilt Thales TH2100A klystron running on a ScandiNova K2 modulator.

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