ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOZGBF4

EVOLUTION OF THE SUPERCONDUCTING LINAC OUTPUT ENERGY AT THE SPALLATION NEUTRON SOURCE*

S-H. Kim†, R. Afanador, D.E. Anderson, D. Barnhart, M. Crofford, B. DeGraff, M. Doleans, J. Galambos, S. Gold, M. Howell, J. Mammosser, C. McMahan, T. Neustadt, C. Peters, M. Plum, J. Saunders, D.J. Vandygriff, D.M. Vandygriff, Oak Ridge National Laboratory, Oak Ridge, USA

Abstract

The SNS linac output energy has increased since the start of neutron production in FY2007. The various improvements that contributed to the increase of the linac output energy are LLRF/control system improvement, high voltage converter modulator system improvement, high-power RF system improvement, cryomodule repairs, spare cryomodule development and accelerating gradient improvement through in-situ plasma processing. In this paper, the history of the SNS SCL output energy is reported, and plans for the near-term future and for the Proton Power Upgrade (PPU) project are also presented.

INTRODUCTION

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory is the world's most powerful accelerator-based pulsed neutron source in operation that provides neutrons for probing material structures and properties. The SNS accelerator consists of a 1-GeV linac, and accumulator ring and various beam transport lines [1]. The superconducting linac (SCL) provides the major portion of the beam acceleration and is considered the backbone of the SNS accelerator. The SNS SCL houses eighty-one SRF cavities in twenty-three cryomodules, eleven of which contains three SRF cavities with geometric beta of 0.61 in each structure, and twelve of which contains four SRF cavities with geometric beta of 0.81 in each structure. The SNS SCL is the world first mega-watt class hadron linear accelerator using superconducting radio-frequency (SRF) technology. Many performance and reliability required a learning curve, and it took time to understand the systems as a whole, and to determine the need for additional performance improvements [2].

The SCL system performance determines the beam energy at the target. Since the SNS operation for neutron production for users started, the beam energy at 60 pulses-per-second (pps) operation has evolved from 850 MeV to near 1 GeV. In the following sections, various efforts to achieve higher beam energy at the target are introduced while pursuing higher beam power and higher beam availability.

EARLY STAGE OF OPERATION

Qualifying the components as a fully integrated system, and identifying and understanding the limiting conditions are critical to achieve reliable operation of cryomodules. Since most sub-systems were not commissioned for the operation at the full duty factor in the early stage of the SNS operation, the RF repetition rate was limited to 15 pps or less in FY07, thus stable accelerating gradients for all the SRF cavities were initially established at 15 pps. At a repetition rate of 15 pps, the average limiting gradients of the medium- and the high-beta cavities are 16.7 MV/m and 17.5 MV/m respectively, which exceed the design gradients. At 15 pps or lower, the individual limiting gradient that is measured by powering one cavity in a cryomodule at a time, are about the same as collective limits that are measured while operating all the cavities in a cryomodule simultaneously. Linac output energy of 1 GeV at 15 pps was first achieved in February 2007.

At a repetition rate of 30 pps or higher, the limiting gradients are reduced related to the thermal load from electrons due to field emission and multipacting. Clear evidence of collective effects limiting the operating gradients of the SRF cavities has been observed at a repetition rate of 30 pps and higher. The severity of the collective effects is not only determined by the amplitude of the accelerating gradients in the cavities of a cryomodule, but also by their relative RF phases because both affect the trajectories of the electrons, energies of the electrons and the locations where the electrons impact on the cavity surfaces. Due to the collective effects, cavities become thermally unstable at lower gradients than the ones at lower repetition rate operation, thus limiting the final Linac output energy.

The early stage of operation had been also dedicated for system learning including peculiar behaviors of sub-components such as cold cathode gauges and higher order mode couplers. Observations and physical conditions near the HOM couplers imply that HOM coupler failures or degradation seem to be a result of electron activity originating from multipacting, field emission, and even gas discharge at the fundamental mode. Several cavities showed odd or excessive signals from HOM couplers and were consequently operated at reduced accelerating gradients or turned off. Interlocks and machine protections have been improved based on results from the qualification studies and from the accumulated operational experience.

Operation at 60 pps was established in FY08. Each cavity was set at a maximum gradient based on the collective limit of gradients rather than setting uniform gradients as designed.

During the early stage of operation, the High Voltage Converter Modulators (HVCMs) were not reliable at the design voltage and the full duty factor. They were operated at a reduced voltage that resulted in a maximum available RF power of 450-500kW rather than the design value of 550kW. Dozens of cavities were limited by lack of RF power at the design beam current. In 2009, one additional

* ORNL is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the US Department of Energy. This research was supported by the DOE Office of Science, Basic Energy Science, Accelerator and Detector Research Program.
† kimsh@ornl.gov

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOZGBF4

HVCM was installed to relieve loads on the HVCMs and to thus increase the HVCM voltage, which increased the linac output energy by 35 MeV.

ERRANT BEAM

Performance degradation that could be related with beam, was first recognized in a few cavities during operation in 2009. After an intensive investigation, it was found that 'errant beam' was the root cause of this issue. The term 'errant beam' at SNS refers to beam lost in the SCL from off-energy beam generated mostly by upstream warm linac RF cavity faults or by oddly shaped beam pulses from the ion source. The errant beam remains from the start of a faulty condition until beam abortion by the machine protection system. The beam energy deposited on SRF cavity surfaces desorbs gas that can create a discharge condition.

The severity of an event depends on the location where the errant beam is lost, duration of the errant beam, and the frequency of events that are associated with the condition of errant beam sources (warm linac and ion source). The average number of errant beam events in the past at SNS was about 30–40 times out of five million daily pulses. Most errant beam events result in beam loss monitor trips and sometimes small vacuum excursions. However, when similar events occur multiple times, there is a chance that an errant beam event might lead to larger vacuum excursions and a following RF interaction could create an environment for severe discharge or arcing. The energy of one mini pulse (about 1 μs beam) at the SNS is up to 24 J. Since the beam loading in the SNS superconducting RF cavities is high, the available RF power (550 kW) is large enough to create a dangerous discharge. Unwanted consequences from errant beam events could be additional gas/particulate contamination or surface damage that leads to RF performance degradation. Component damage is also possible, such as failures of power coupler ceramic windows. Various improvements have been implemented to minimize the number of errant beam events, such as careful conditioning for the ion source and the warm linac cavities, routine maintenance of vacuum systems, and continuous adjustment of operating parameters for warm linac cavities. Presently, the frequency of errant beam events is less than 10 times per day. In addition, a new dedicated protection system to abort the beam within 8 μs has been developed and integrated into beam operation [3].

REPAIRS AND SPARE CRYOMODULE

Cryomodule repair activities continue to sustain cryomodule performance and reliability. The repair and recovery of cryomodules includes: thermal cycling, removal of piezo tuners and HOM coupler feedthroughs, replacement of damaged parts such as fundamental power couplers, instrumentation, and repair of leaks developed during operation. Six cryomodules have been removed from the tunnel for repairs since FY07.

The SNS established, as a priority, the capability to perform in-house repairs to SCL systems. This includes the rework and repair of cryomodules, development of spare cryomodules, research and development focused on improving existing cryomodule performance, and support for the 1.4 MW operation as well as future upgrades for increased capability.

One spare high beta cryomodule was developed by in-house SNS resources and has been in service for neutron production since summer 2012. All four cavities in this cryomodule are running at 16 MV/m limited by available RF power and do not show measurable x-rays while running at 16 MV/m. The spare high beta cryomodule allows removal of an operating high beta cryomodule for complex repairs while maintaining the same beam energy. Rework is the only option for the unrecoverable damages of cavity surface and parts. There were some design changes for the spare high beta cryomodule to comply with the pressure vessel requirements. The development of a spare medium beta cryomodule is in progress using the same design concept as for the high beta spare. These design changes will be also incorporated in the cryomodules for the SNS Proton Power Upgrade (PPU) Project.

IN-SITU PLASMA PROCESSING FOR PERFORMANCE IMPROVEMENT

From 2009 to 2012 the linac output energy achieved had been 930 MeV. This energy level was set based on the collective limits found at 60 pps and following addition adjustments from operational experiences. The energy was increased to 940 MeV by installing the spare high beta cryomodule in the place of the worst performing cryomodule.

A 15% additional beam acceleration in the high beta cavity section of the SCL was required to reach 1-GeV operation with an energy reserve. In-situ processing of SRF cavities in the tunnel was identified as an important area of research to improve the performances of the SNS SRF cavities while minimizing the impact on machine operation and reducing cost for the improvements. R&D for in-situ processing using plasma has successfully demonstrated that the accelerating gradients in operating cavities can be increased by 2 MV/m or higher on average [4].

The plasma processing developed at the SNS mainly focuses on removal of residual hydro-carbons using low density reactive oxygen plasma at room temperature. The technique has so far been successfully applied to cavities in the horizontal test apparatus, cavities in one off-line cryomodule and cavities in seven of the cryomodules in the tunnel. After applying in-situ plasma processing, reductions of field emission, multipacting, vacuum activities and thermal load in the end group have been observed. The linac output energy was increased to 990 MeV after deploying the in-situ technique on four cryomodules in the tunnel. The in-situ plasma processing for three additional high beta cryomodules was completed in April 2018. Improvements of the SRF cavities in these three cryomodules are being measured. It is notable that no degradation has been observed after deploying the in-situ plasma processing so far.

HISTORY OF SNS BEAM ENERGY

Figure 1 plots the SNS linac output energy at 60-pps operation since FY08. In this figure the numerical labels correspond to the following descriptions:

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOZGBF4

1) early stage learning curve, repair of two cryomodules, and improvement of LLRF/control system for operation to avoid nuisance cavity trips;

2) addition of one HVCM for high beta SRF cavities, which increased available RF power for each SRF cavity to the full design RF power of 550 kW and shortened the cavity fill time to 250 µs;

3) first recognition of potential damages from errant beam discussed in the previous section;

4) one cavity in each beta region disabled due to vacuum leak through the FPC ceramic windows;

5) one high beta and one medium beta cryomodules out from the tunnel for FPC replacements;

6) the spare high beta cryomodule is installed in the SCL in replacement of the high beta cryomodule removed during the same outage as item 5);

7) one medium beta cryomodule back to service after FPC replacement;

8) several SRF cavities at slightly lower gradients for the operation at the full duty factor;

9) replacement of the worst performing high beta cryomodule with the offline high beta cryomodule after FPC replacement;

10) application of the in-situ plasma processing to a high beta cryomodule;

11) application of the in-situ plasma processing to another high beta cryomodule;

12) application of the in-situ plasma processing to two additional cryomodules;

13) application of the in-situ plasma processing to three additional cryomodules;

The qualification of cavity performance after item 13) is in progress as of April 2018 and the output energy is expected to be 1 GeV with an increased energy margin.

SCL STRATEGY FOR PROTON POWER UPGRADE PROJECT

The beam power of the linac for the PPU will be doubled to 2.8 MW. Beam current will be increased by ~50%, and seven additional cryomodules will be installed in the reserved space at the end of the linac tunnel to produce linac output energy of 1.3 GeV [5]. The design accelerating gradient of the new cavities for PPU is 16 MV/m and each cavity will be fed by a 700-kW klystron.

The High Power RF (HPRF) systems for the existing cavities will be kept the same for economic reasons. Since the output power at saturation of existing HPRF systems is 550 kW, accelerating gradients of high performing high beta cavities need to be lowered for the PPU beam loading. The accelerating gradients of the existing cavities for the PPU baseline assumes some of gradients for medium beta cavities will be increased by plasma processing to better utilize the available RF power in medium beta section.

SUMMARY

Significant testing and operational experience has led to a better understanding of systems and their limiting conditions in pulsed mode operation. The knowledge gained at high duty factor operation has been used to prioritize tasks for better reliability and additional performance improvements.

SNS has conducted a multi-faceted approach to increase the linac output energy to reach 1-GeV operation while keeping the machine highly reliable. Through various efforts, the linac output energy has been progressively increased toward this goal. The availability of SRF cavities, cryomodules and cryo-plant has been 99% or higher for the last seven years.

REFERENCES

[1] S. Henderson *et al.*, "The Spallation Neutron Source accelerator system design," *Nucl. Instr. Meth A*, vol. 763, pp. 610-673, 2014, doi: 10.1016/j.nima.2014.03.067

[2] S. Kim *et al.*, "Overview of ten-year operation of the superconducting linear accelerator at the Spallation Neutron Source," *Nucl. Instr. Meth. A*, vol. 852, pp. 20-32, 2017, doi:10.1016/j.nima.2017.02.009

[3] W. Blokland and C. Peters, "A new differential and errant beam current monitor for the SNS accelerator." In *Proc. 2nd International Beam Instrumentation Conference 2013*, Oxford, UK, pp. 921-924.

[4] M. Doleans *et al.*, "In-situ plasma processing to increase the accelerating gradients of superconducting radio-frequency cavities," *Nucl. Instr. Meth. A*, vol. 812, pp. 50-59, 2016, doi: 10.1016/j.nima.2015.12.043

[5] S. Kim *et al.*, "Superconducting linac upgrade plan for the second target station project at SNS," in *Proc. SRF'15*, Whistler, Canada, pp. 268-271.

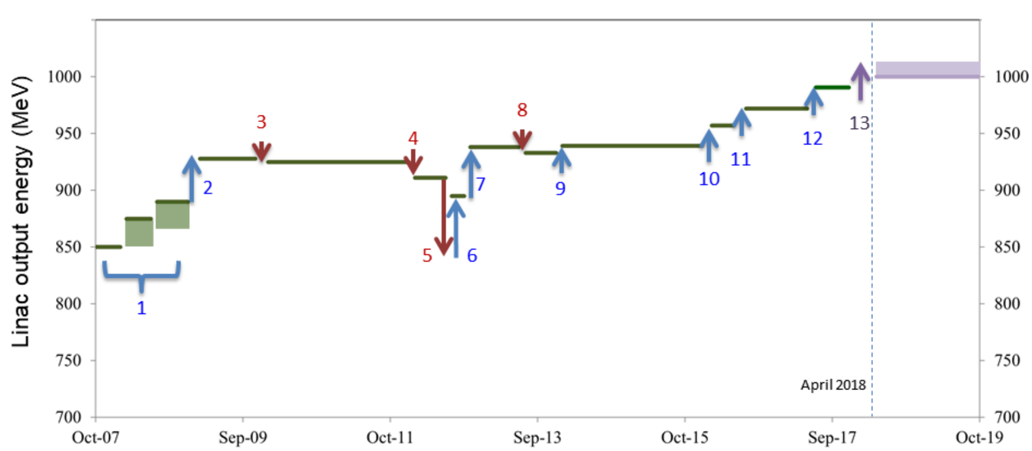

Figure 1: SNS beam energy history since FY08.