

RELIABILITY ANALYSIS OF SNS SRF LINAC AND PERSPECTIVE FOR FUTURE HIGH-POWER PROTON SRF LINACS*

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Abstract

Future proton superconducting RF (SRF) linacs used as accelerator driven systems (ADS) must achieve high reliability and availability to meet the challenging parameters for applications in medical treatment, nuclear waste reduction, and nuclear electricity generation. What SRF innovations and advanced concepts are needed? To answer this question, a case study of the past, current, and possible future downtime sources is carried out for the Spallation Neutron Source (SNS) SRF linac (SCL) systems. The preliminary outcome of this study is presented. We will discuss its implications to the needed development of the next generation SRF systems and related systems towards >10 MW proton SRF linacs required for future ADS facilities.

INTRODUCTION

SNS is an accelerator-driven neutron source facility. Its accelerator system design is described in Ref. [1]. The SNS linac systems (see Fig. 1) consists of the Front End (FE), the normal conducting Drift Tube Linac (DTL), the normal conducting Coupled Cavity Linac (CCL), and the SRF linac (SCL). Two families (medium-beta $\beta=0.61$ & high-beta $\beta=0.81$) of 6-cell 805 MHz SRF niobium cavities are placed in 11 medium-beta (3 cavities per module) and 12 high-beta (4 cavities per module) cryomodules, accelerating the H^- beam from 186 MeV to 1 GeV.

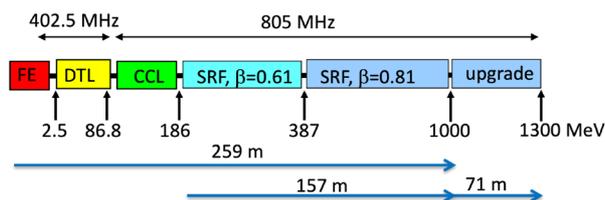


Figure 1: The SNS linac system.

SNS is routinely operated at a 1.4 MW beam power with a 99% availability in its SRF systems [2] and is currently undergoing an upgrade to a new level capable of a 2.8 MW beam power. Seven new high-beta cryomodules (28 new cavities) are to be added at the completion of the on-going SNS Proton Power Upgrade (PPU) project, raising its linac energy output to 1.3 GeV [3].

Future proton SRF linacs used as accelerator driven systems (ADS) must achieve high reliability and availability to meet the challenging parameters for applications in medical treatment, nuclear waste reduction, and nuclear electricity generation. The long-term operational experience of SNS SCL provides a reference for identifying the gaps that need to be met. Toward that end, a case study of the past,

current, and possible future downtime sources is carried out for the SNS SRF linac systems. The preliminary outcome of this study is presented. Its implications to the needed development of the next generation SRF systems and related systems towards high-power proton SRF linacs required for future ADS facilities are discussed.

SCL DOWNTIME AND AVAILABILITY

Long-Term Operational Performance

SNS started its neutron production in 2006 (fiscal year FY07). After the initial facility ramp up over a period of five years accompanied by an increasing reliability, a reliable operation of its accelerator systems has been achieved since FY11 sustaining a system reliability of >90%, excluding failures related to the target and the front end RFQ. The reliability analysis of the SNS SCL presented in this paper is based on the downtime data collected over the period of FY11 – FY22 (Oct. 1, 2010 – Sep. 30, 2022).

Down Time Data Collection

SNS down time data are systematically collected in the form of a spreadsheet according to a defined methodology. A sample data piece is shown in Fig. 2 (for brevity, two data columns, one for the shift ID and the other beam on/off status, are omitted). This raw data collected over the period of FY11 – 22 is the basis of our analysis.

ComponentNm	GroupNm	Srf_Mm	Srf_Am	Srf_Am	Srf_Am	Srf_Am	ComponentNm
23-FE-21	FrontEnd	0.000000	0.000000	0.000000	0.000000	0.000000	3.1 1.4375 Coupler cooling system fault
24-DTL-21	Drift Tube Linac	0.000000	0.000000	0.000000	0.000000	0.000000	4.2 2.26 CCL Beam Stop on C3 rotor displacement
25-CCL-21	Coupled Cavity Linac	0.000000	0.000000	0.000000	0.000000	0.000000	3.26 2.26 CCL Beam Stop on C3 rotor displacement
31-SRF-21	SRF System	0.000000	0.000000	0.000000	0.000000	0.000000	1.2 2.26 CCL Beam Stop on C3 rotor displacement, recovery
31-SRF-21	SRF System	0.000000	0.000000	0.000000	0.000000	0.000000	4.6 Recovery from DC voltage trip
18-Mod-21	Cryomodule and Superconducting RF	0.000000	0.000000	0.000000	0.000000	0.000000	1.2 Unplanned shutdown due to CCLRF vacuum leak
18-Mod-21	Cryomodule and Superconducting RF	0.000000	0.000000	0.000000	0.000000	0.000000	1.2 Unplanned shutdown due to CCLRF vacuum leak
25-Age-21	Cryomodule and Superconducting RF	0.000000	0.000000	0.000000	0.000000	0.000000	1.2 Unplanned shutdown due to CCLRF vacuum leak
25-Age-21	Cryomodule and Superconducting RF	0.000000	0.000000	0.000000	0.000000	0.000000	8.1 SCL 1.1.2 Coupled Cavity Fault
18-Age-21	Cryomodule and Superconducting RF	0.000000	0.000000	0.000000	0.000000	0.000000	8.1 SCL 1.1.2 Coupled Cavity Fault
18-Age-21	Cryomodule and Superconducting RF	0.000000	0.000000	0.000000	0.000000	0.000000	8.1 SCL 1.1.2 Coupled Cavity Fault

Figure 2: A sample piece of raw SNS down time collected.

Hierarchy

At the top level of the raw data hierarchy is the Group Name (Group_Nm) which is somewhat mirrored to the group responsible for the maintenance and functioning integrity of a given sub-system. While such a hierarchy is helpful in facilitating resource allocation from the operation organizational point of view, it does not always provide a useful platform for gaining insight into the dependences across the systems or sub-systems that is important for accelerator reliability analysis. For that reason, we constructed a new hierarchy oriented to logical dependences. Automatic data processing based on a Python program is carried out in mapping the raw data in the standard hierarchy to the more useful data in the new hierarchy. Downtime events occurred when there was no beam were rejected from our analysis.

There are five hierarchical levels: (L1) System; (L2) Sub-System; (L3) Device System; (L4) Sub-Device-

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System; (L5) Device Name. For the results presented in this paper, the SCL system is at L1. At L2, there are 11 sub-systems including

- Cryomodule & SRF
- SCL HPRF (High-Power RF)
- SCL LLRF (Low-Level RF)
- SCL HVCM (High Voltage Conversion Modulator)
- SCL Cryogenics
- SCL Vacuum System
- SCL Control System
- SCL Beam Instrumentation
- SCL Beam Loss, SCL Magnet
- SCL Machine Protection.

Figure 3 shows the SCL downtime sources by sub-systems over the period of FY11-FY22. The leading sources are SCL HVCM, Cryomodule and SRF, SCL HPRF, and SCL Cryogenics.

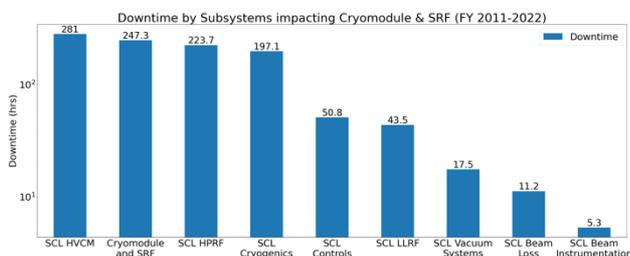


Figure 3: SCL downtime sources by sub-systems.

At L3 under Cryomodule and Superconducting RF, there are 23 cryomodules (CM1...CM23). Top 5 downtime cryomodule device sources are CM1(42 hours), CM19(35.4 hours), CM6(28.9 hours), CM2(27 hours), and CM21(25.5 hours) over the period of FY11-FY22.

At L4 under each Cryomodule Device, there are 7 sub-device systems including SRF Cavity & Structure, Insulating Vacuum, Beamline Vacuum, RF Coupler, HOM Coupler, Tuner, and Heater. Fig. 4 shows the downtime sources by sub-device systems for all cryomodules. The leading source is the SRF Cavity & Structure, followed by the Beamline Vacuum. More detailed analysis on the fault types related to the SRF Cavity & Structure are given in the next section.

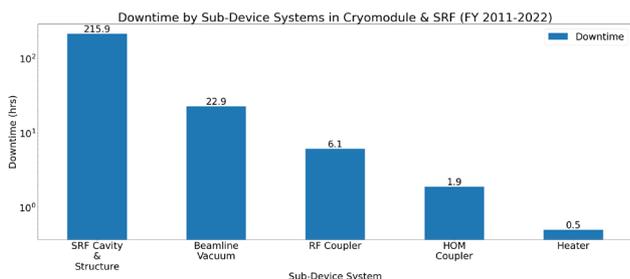


Figure 4: Downtime sources by sub-device systems for all cryomodules operated for neutron production runs.

Finally, at L5, unique device names are specified such as Cavities (1a...23d), Cold Cathode Gauges, Ion Pumps, and Gate Valves.

Availability

The availability is the accumulated uptime (in hours) divided by the published neutron production hours. Fig. 5 shows the availability trend of the SRF Cavities/Cryomodules and the SCL Systems over the period of FY11-FY22. On average, a 99.55% and 97.95% availability were delivered over the 12-year period from FY11 to FY22.

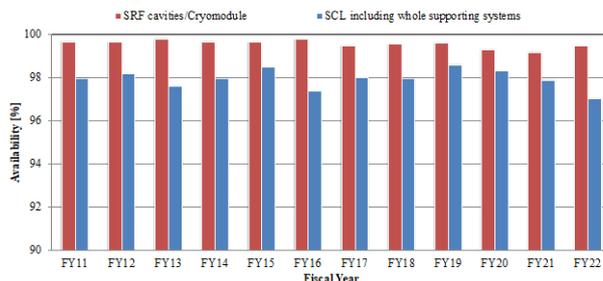


Figure 5: Availability trend of SRF Cavities/Cryomodules and the SCL systems including supporting systems.

SCL FAULTS

Fault Types

Each downtime event has an apparent cause originated from a sub-device system or a device as detected by some sensors. The column “Notes” in the raw downtime data (see Fig. 2) is the main source for the apparent cause. We defined 20 fault SCL types as shown in Table 1.

Table 1: SCL Downtime Fault Types

#	Fault Name
1	Chatter Fault
2	Beamline Vacuum Fault
3	Quench Fault
4	Higher Order Mode Fault
5	Cryogenics Fault
6	LLRF Fault
7	Field Clipping Fault
8	Klystron Power Fault
9	RF Window Vacuum Fault
10	RF Coupler Fault
11	BLM Trip Fault
12	Cavity Field Fault
13	Cavity Reflected Power Fault
14	Heater Fault
15	Midnight Arc Test Fault
16	Tuner Mechanical Fault
17	Tuner Control Fault
18	HPM Fault
19	RF Window Arcing Fault
20	Other Faults

Fault type identification is carried out automatically in the Python program by seeking key word or a combination of key words following a specific Boolean operation. For

examples, a Chatter Fault is identified if the single key word “chatter” is detected; a Beamline Vacuum Fault is identified if “vacuum” or “SGV” or “burst” or “spike” is detected AND no key word “chatter” is detected concurrently. This task turned out to be quite tedious as the content in the “Notes” column can be dependent on its creators (namely the machine operators) and is prone to human errors (such as typos). Nevertheless, with our choice of fault types, it is now possible to gain insight into the leading fault types in Cryomodule & SRF downtime as shown in Fig. 6. As can be seen, Chatter Fault is by far the dominant fault type, followed by Cavity Field Fault, Vacuum Fault, and Quench Fault etc.

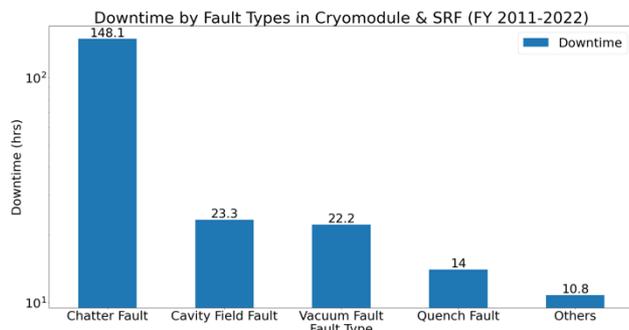


Figure 6: Top 5 fault types in Cryomodule & SRF.

Chatter Faults

The Chatter Fault is further broken down into 14 sub-types with top 10 of them shown in Fig. 7.

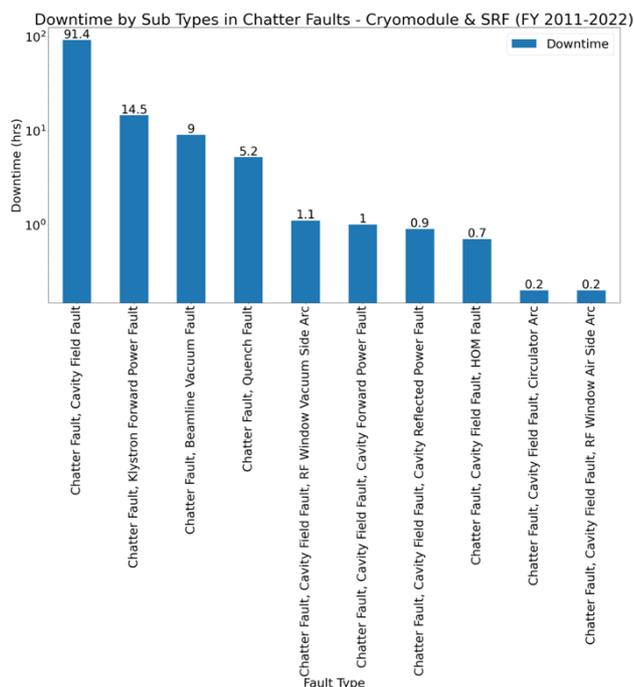


Figure 7: Top 10 sub-chatter-fault types in Chatter Fault.

The leading sub-chatter-fault is Chatter with Cavity Field, followed by Chatter with Klystron Forward Power, Chatter with Beamline Vacuum, Chatter with Quench, and

more complex chatter faults involving the cavity field and a non-cavity component such as the RF window, the RF power coupler, the HOM coupler, or even some remote component such as a circulator.

IMPLICATIONS TO FUTURE HIGH-POWER SRF LINACS

The SNS long-term neutron production operation delivered a 99.55% average availability in its SCL systems over a period of 12 years. This hints a bright prospect for the future high-power proton linacs based on SRF technology. For SNS SCL, the top four downtime sources are HVCM, Cryomodule & SRF, HPRF, and Cryogenics. Future 10-20 MW ADS machines will be operated in the CW mode, The HVCM downtime is not expected to play a role in the machine reliability if klystrons are replaced by solid state RF sources down the road. The major development required would be in areas of Cryomodule & SRF, HPRF, and Cryogenics. The SCL Control, LLRF, and Vacuum sub-systems contributed also sizably to the SNS downtime. We anticipate those areas are of interest as well.

Within the domain of SNS Cryomodule & SRF, the leading fault types are Chatter Fault, Cavity Field Fault, Vacuum Fault, and Quench Fault. It is an open question as to whether a Chatter Fault has its root in the pulsed operation mode of SNS or if it is relevant to future high-power CW SRF linacs. Nevertheless, the SNS experience does seem to suggest the importance of the SRF cavity field control and its interplay with the cavity quench limit and the beamline vacuum conditions.

The resonant frequency of SNS SRF cavities is 805 MHz. The relatively large aperture along with a modest operation gradient of SNS SRF cavities as compared to the mainstream L-band SRF technology [4,5] appeared to be a beneficial factor, contributing to the reliable SNS operation. Future high-power proton SRF linacs may further benefit from even larger cavities. The chosen frequency of 650 MHz for elliptical SRF cavities in the PIP-II project [6] seems to be in the right direction. The optimal SRF cavity frequency seems to be still open.

CONCLUSION

We carried out a systematic analysis of the downtime collected in the SNS SCL systems over a 12-year period for reliable neutron production. Leading downtime sources and key fault types are identified. This analysis has given us bright prospect in the future high-power ADS facilities based on the SRF technologies. We identified the interplay between SRF and HPRF, Cryogenics, Control, and LLRF to be a main area for future development. Further analysis is under way on the downtime events automatically collected by the machine protection systems which allows resolving fast trips. That effort, along with the investigation of fast trip events captured by the diagnostic systems, is expected to shed further light on the needed development towards the future high-power proton SRF linacs for applications in medical treatment, nuclear waste reduction, and nuclear electricity generation.

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